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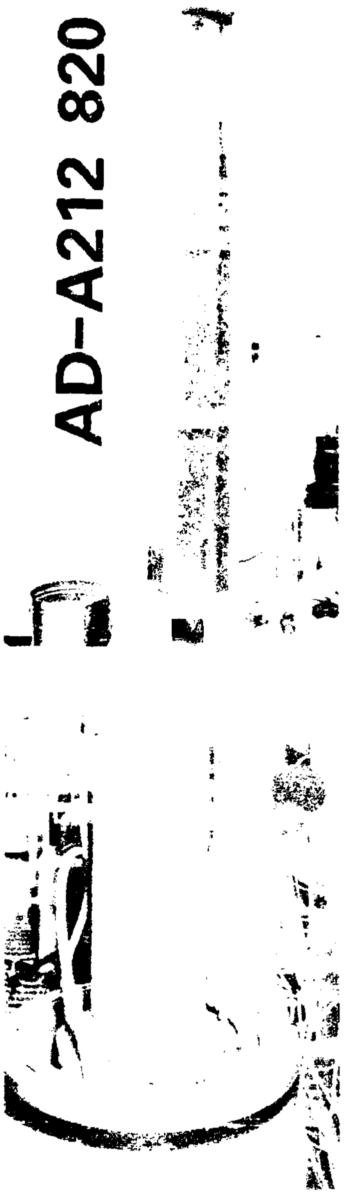

MISCELLANEOUS PAPER GL-89-15

ACOUSTIC EMISSION MONITORING OF COFFERDAM PERFORMANCE, LOCKS AND DAM 26 (REPLACEMENT)

by

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September 1989

Final Report

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A research program consisting of measuring acoustic (microseismic) emissions generated on and within the circular cofferdam cells was conducted. The purpose of the study was to correlate the acoustic emissions with the forces acting on the cofferdam and the resulting movements and stresses caused by such forces.

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PREFACE

This report was prepared by Ground Engineering, Inc., St. Louis, Missouri, under contract to the US Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, for the US Army Engineer District, St. Louis. The report was prepared under Contract No. DACW39-86-C-0048.

This report was reviewed by Mr. G. Britt Mitchell, Chief, Engineering Group, Soils Mechanics Division (SMD), Geotechnical Laboratory (GL), WES. General supervision was provided by Mr. Gene P. Hale, Acting Chief, SMD, and Dr. William F. Marcuson III, Chief, GL.

Acting Commander and Director of WES during preparation of this report was LTC Jack R. Stephens, EN. Dr. Robert W. Whalin was Technical Director.

1.0 INTRODUCTION

A research and development program has been conducted over a two year period since March 1986 in connection with the construction of Locks & Dam 26 (Replacement) Phase II on the Mississippi River at Alton, Illinois. This program consisted of measuring and recording acoustic (microseismic) emissions generated at and within the circular cells of the construction cofferdam. The Study has attempted to correlate the acoustic emissions (AE) with the forces acting on the cofferdam and the resulting movements and stresses caused by such forces. The following report discusses the purpose, goals and objectives of the Study; acoustic emission theory; equipment used; site data; and Study chronology. It also includes a summary of the data obtained during the Study, provides an analysis of the data, and develops conclusions and recommendations.

2.0 GOALS AND OBJECTIVES

The general objective of the Study was to explore the way in which a program of AE measurements could be used to provide a practical and relatively simple method of monitoring the performance and safety of the Phase II cofferdam and other similar structures. A further series of objectives included a Study of the use of the AE method to measure relative stress conditions in the granular backfill of the sheet pile cells, the internal soil reaction to cell distortions during high river stages, and the response of different components at various locations in the

cellular structure as it was subjected to a wide variety of loading conditions.

Additional goals included the correlation of AE data with the results of other engineering measurements and monitoring devices, such as pile movement points (PMP) installed at various locations in the cofferdam and an analysis to determine if a practical and effective method of monitoring the performance and safety of future cofferdams could be developed.

3.0 ACOUSTIC EMISSION OVERVIEW

3.1 Background

Acoustic emissions (AE) are generally subaudible sounds generated by the release of strain energy within a material as it is stressed and undergoing deformation. Sometimes these sounds are audible (wood cracking, ice expanding, soil and rock particles abrading against one another, etc.), but more often they are not, due to their low amplitude or high frequency, or both. A piezoelectric sensor is used as a "pickup" to detect the emissions. This transducer produces an electrical signal proportional to the amplitude of sound or vibration being detected. The signal is amplified, filtered, and counted or recorded in some quantifiable manner. Unwanted construction equipment, extraneous and ambient noises are electronically filtered from the signal or separately quantified and subtracted from the test results. The count rate or recordings of the emissions are then correlated with the basic material behavior to empirically determine the relative stability of the material

being tested. If no AE emissions are generated, then the material is stable and equilibrium conditions can be assumed to exist. If, however, a large number of emissions are observed, a nonequilibrum situation exists which may eventually lead to failure.

It should be mentioned that the technique is not new; only its application to soil masses and related Civil Engineering problems is new. The original geotechnical literature and references date back to the late 1960's(1). Of particular interest is the work done in the mining industry. The leading organization appears to be the U.S. Bureau of Mines, but excellent work has been reported in Canada, West Germany, Poland, Russian, Australia and Japan. Many of these projects have been described in the proceedings of four conferences held at the Pennsylvania State University in 1975, 1978, 1981 and 1985.(2)

3.2 System Components

The components of an acoustic emission monitoring system generally consist of a wave guide (to bring the signals from within the soil to a convenient monitoring point); sensor (geophone, accelerometer, hydrophone or other type of transducer) to convert the mechanical wave to an electrical signal; preamplifier (to amplify the signal if a long cable is being used); filters (to eliminate undesirable portions of the signal); amplifier (to further amplify the signals for processing); and a quantification system. The quantification system is usually some

form of counter. The following methods have been used:

* ringdown counts (or count rate); see Fig. 6.3 for a schematic representation of ringdown count occurrence.
* event counts (or event rate)
* amplitude (or amplitude distribution)
* energy (RMS or other type of analysis)
* rise time
* frequency analysis

In general, AE monitoring systems use total counts or count rate, or total events or event rate, (also called threshold crossings or ringdown counts) for quantification. The variation of equipment configuration can obviously be great which leads to many possible systems. Currently a number of companies manufacture single channel AE systems for geotechnical use (Acoustic Emission Technology Corp., Dunegan/Endevco, W. Nold Co., Slope Indicator Co., Weston Geophysical Corp.) and several make multi-channel systems (Acoustic Emission Technology Corp., Physical Acoustics Corp., and Slope Indicator Co.). The equipment used in this Study and its configuration is described in Section 4, Equipment and Installation.

3.3 Major Characteristics of AE in Soils

Three items are of prime interest when considering AE monitoring of soil systems. The following discussion is also applicable to AE monitoring of materials where plane surface friction is the predominate AE source mechanism, e.g., steel sheet piling. The generation of an acoustic emission signal from a deforming frictional based material is a process which is quite

complex and has only been estimated on a peripheral basis. Using a concept based on physical fundamentals, Lord and Koerner (3) have derived the following relationship:

$$a_{max} = \left(\frac{\pi f^2 e^2 VRc}{2 \pi t r^2}\right)^{1/2}$$

where

a = acceleration	R = radiation efficiency
f = frequency	c = wave velocity
e = elastic strain	t = transfer time (source to pickup)
V = volume	r = distance from source

The above must be used with caution since it represents, at best, a first approximation of the process.

Considerably more effort has recently been placed on frequency analysis of the resulting AE signals.(4,5) By tape recording the signals from stressed soils in unconfined compression and triaxial shear and playing them through an octave band filter, the predominate frequencies have been found to be from 250 Hz to 8,000 Hz. However, this is also the frequency range of ambient or background noise such as that caused by traffic, construction equipment, etc. Since attenuation of signal strength increases in direct proportion to frequency, selection of the most practical frequency requires a trade-off between ambient noise interference and signal attenuation. In general, sensors in the 30 to 150 kHz range have been found most suitable for use in monitoring AE generated in stressed soil systems. Sensors whose resonant frequency is in the lower portion of this range are usually more responsive. The decay of signal strength, or attenuation, of an AE wave as it passes through soil is relatively high, and is strongly frequency dependent. Using a number of measurement techniques, the value has been found to be

between 7 and 27 dB per meter in the frequency range of interest. Note should be made that this attenuation is two orders of magnitude larger than in metal, thus the use of a steel wave guide to bring the AE signals to a pickup point is highly desirable. This feature will not be necessary when monitoring steel sheet piles since the piling can function as its own wave guide.

3.4 References

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2. Hardy, H.R. Jr., and F.W. Leighton, Eds., Proceedings of First and Second Conferences on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, Pennsylvania State University, 1977, 1979 and 1984, Trans.Tech.Publ.
3. Lord, A.E. Jr. and Koerner, R.M., "Estimated Magnitude of Acoustic Emissions in Soils", Journal of Geotechnical Engineering Division, ASCE, Vol. 105, No. GT10, Oct. 1979, pp. 1247-1253.
4. Koerner, R.M., Lord, A.E. Jr., McCabe, Wm. M. and Curran, J.W., "Acoustic Emission Behavior of Granular Soils", Journal Geotechnical Engineering Division, ASCE, Vol. 102, No. GT7, July, 1976, pp. 761-773.

5. Koerner, R.M., Lord, A.E. Jr., and McCabe, W.M., "Acoustic Emission Behavior of Cohesive Soils", Journal Geotechnical Engineering Division, ASCE, Vol. 103, No. GT8, Aug. 1977, pp. 837-850.

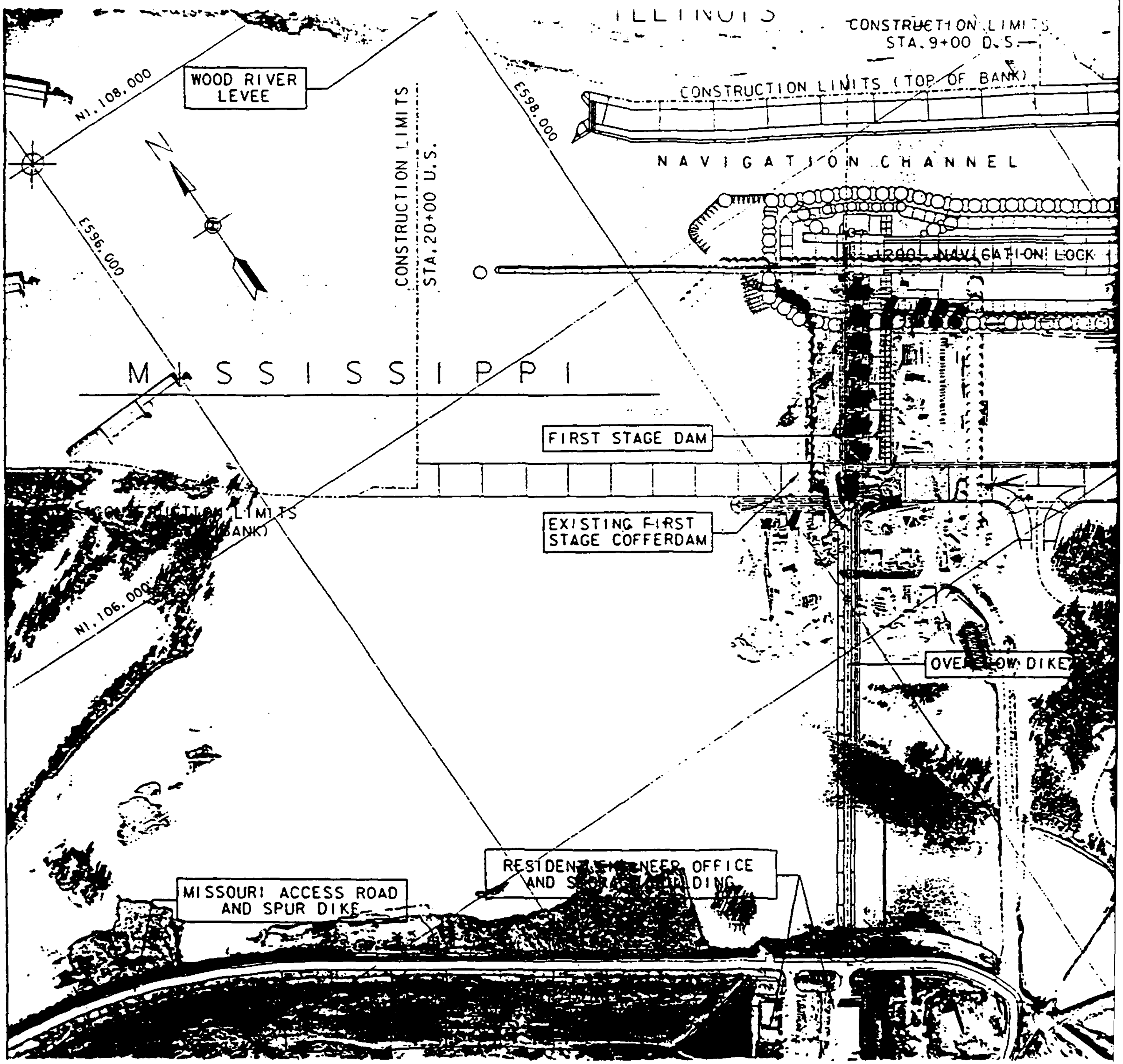
4.0 SITE CONFIGURATION

Locks & Dam 26 (Replacement) has been under construction since 1979. It is located at mile 200.78, on the Mississippi River approximately two miles downstream from existing Locks & Dam 26 near Alton, Illinois, which is to be demolished upon completion of the new structure. Phase I of the project included the construction of five gate bays on the Missouri side of the river. Phase II which includes two gate bays and the first lock was started in 1984. Completion is scheduled for 1992. Construction of each phase has proceeded in the dry within a cellular sheet pile cofferdam. The cofferdams in themselves are major structures which must withstand the force of differential head as great as 68 feet dependent upon Mississippi River elevation. The location, configuration and basic details of the Phase II cofferdam are shown in Figures 4.1, 4.2, 4.3 and 4.4.

As shown on the above figures, the Phase II cofferdam consists of 54 main cells, seven backup cells and six Phase III tie-in cells joined into a continuous structure by sheet pile connecting arcs. Each cell is 63 feet in diameter and is formed by approximately 220 interlocking steel sheet piles. The sheet piles vary in length from 95 to 105 feet and are driven approximately 20 feet below the river bottom. The cells and connecting arcs are filled with dredged river sand and some gravel. The upper two feet consists of graded crushed limestone. The resulting structure forms a continuous protective wall enclosing approximately 25 acres. The eastern line of cells is about 1,000

feet from the Missouri shore and provides a 300 foot wide navigation channel on the Illinois side of the river. Each cell is numbered as shown on Figure 4.2. These numbers will be used throughout the report to refer to locations at which AE were recorded and data collected and analyzed.

FIG 4.1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WOOD RIVER LEVEE
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E598,000
E596,000
N
CONSTRUCTION LIMITS
STA. 20+00 U.S.
NAVIGATION CHANNEL
1200' NAVIGATION LOCK
MISSISSIPPI
FIRST STAGE DAM
EXISTING FIRST STAGE COFFERDAM
N1,106,000
MISSOURI ACCESS ROAD AND SPUR DIKE

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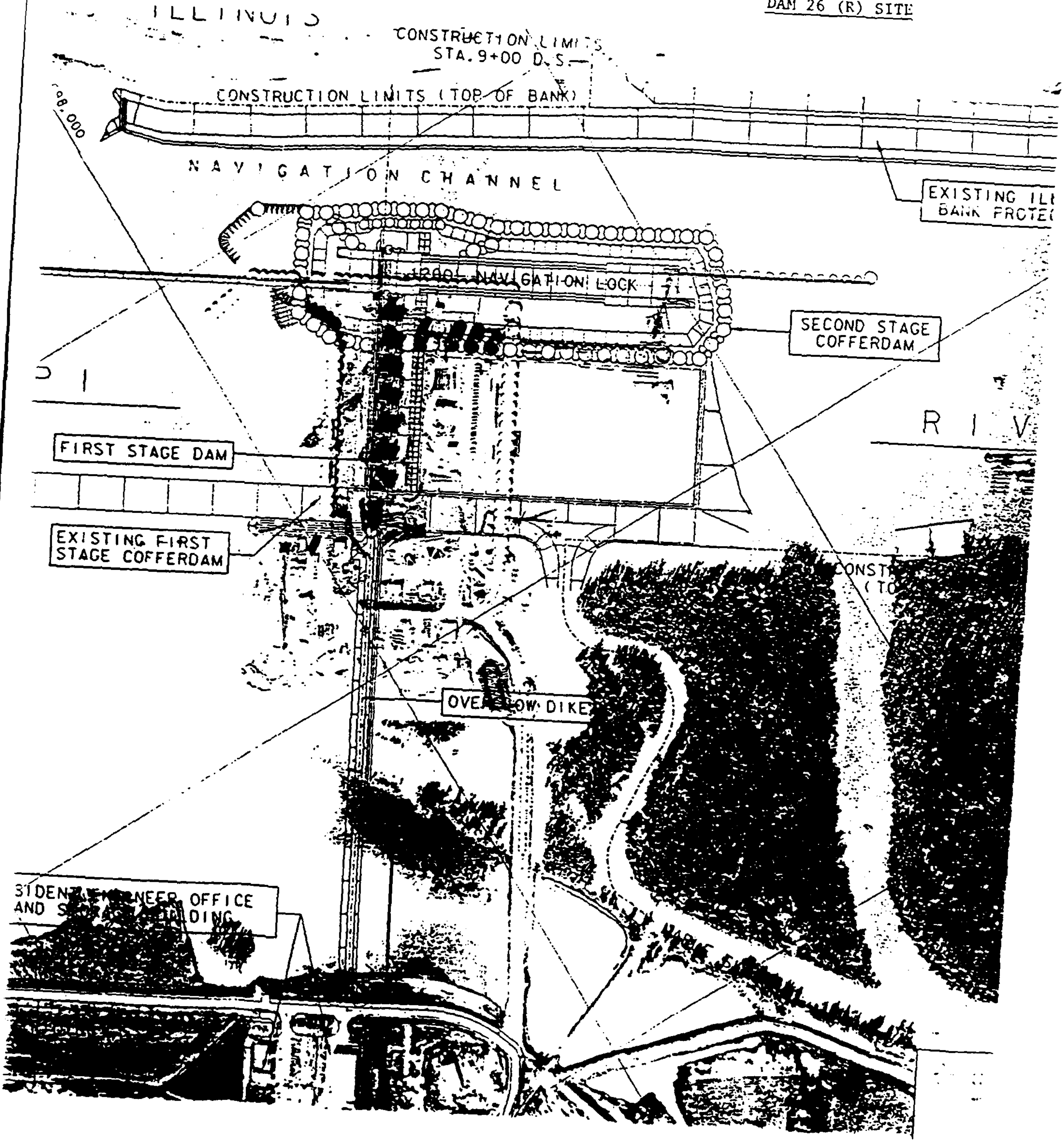
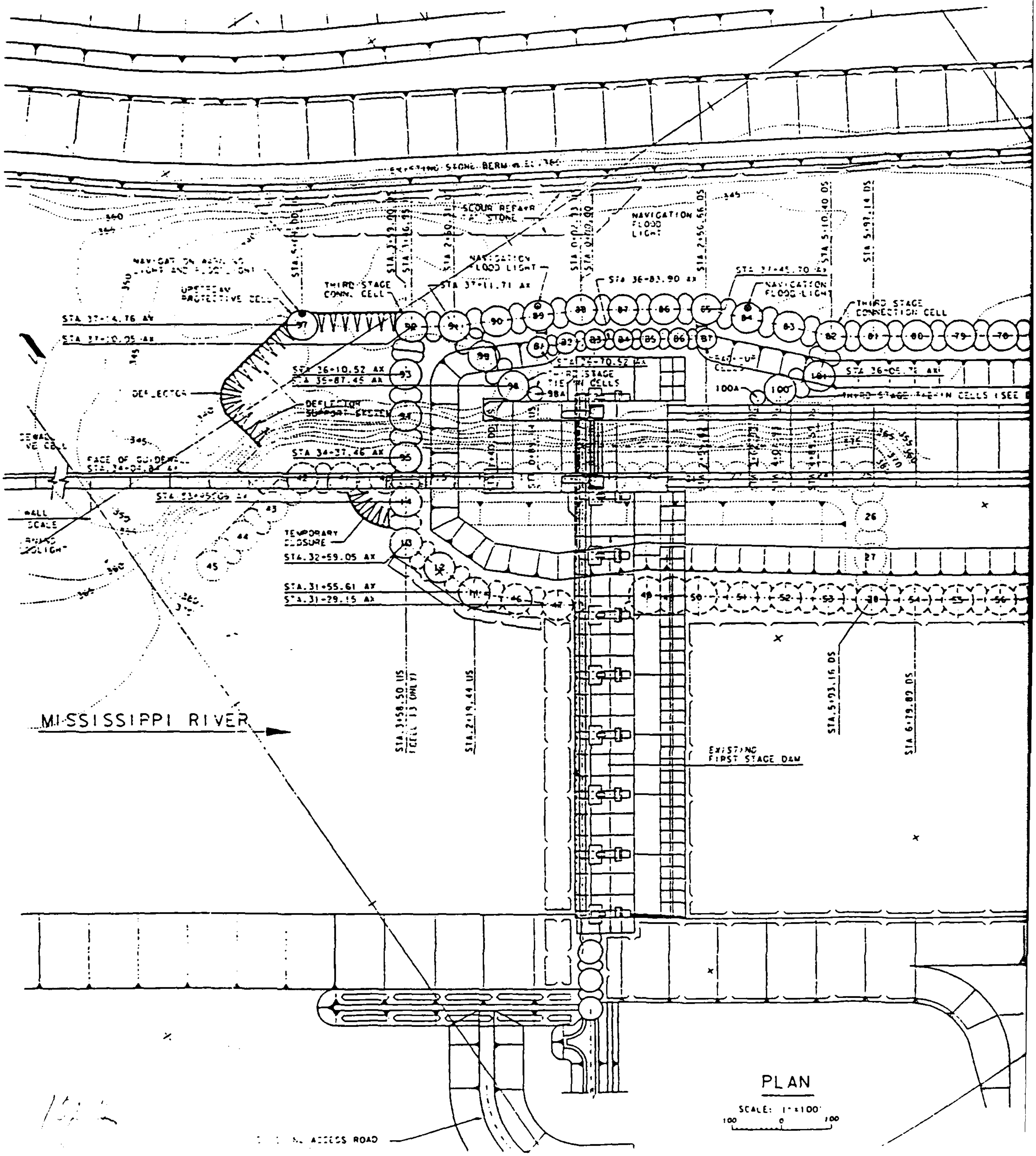
FIG 4.1 AERIAL VIEW (ENHANCED) OF LOCKS AND DAM 26 (R) SITE

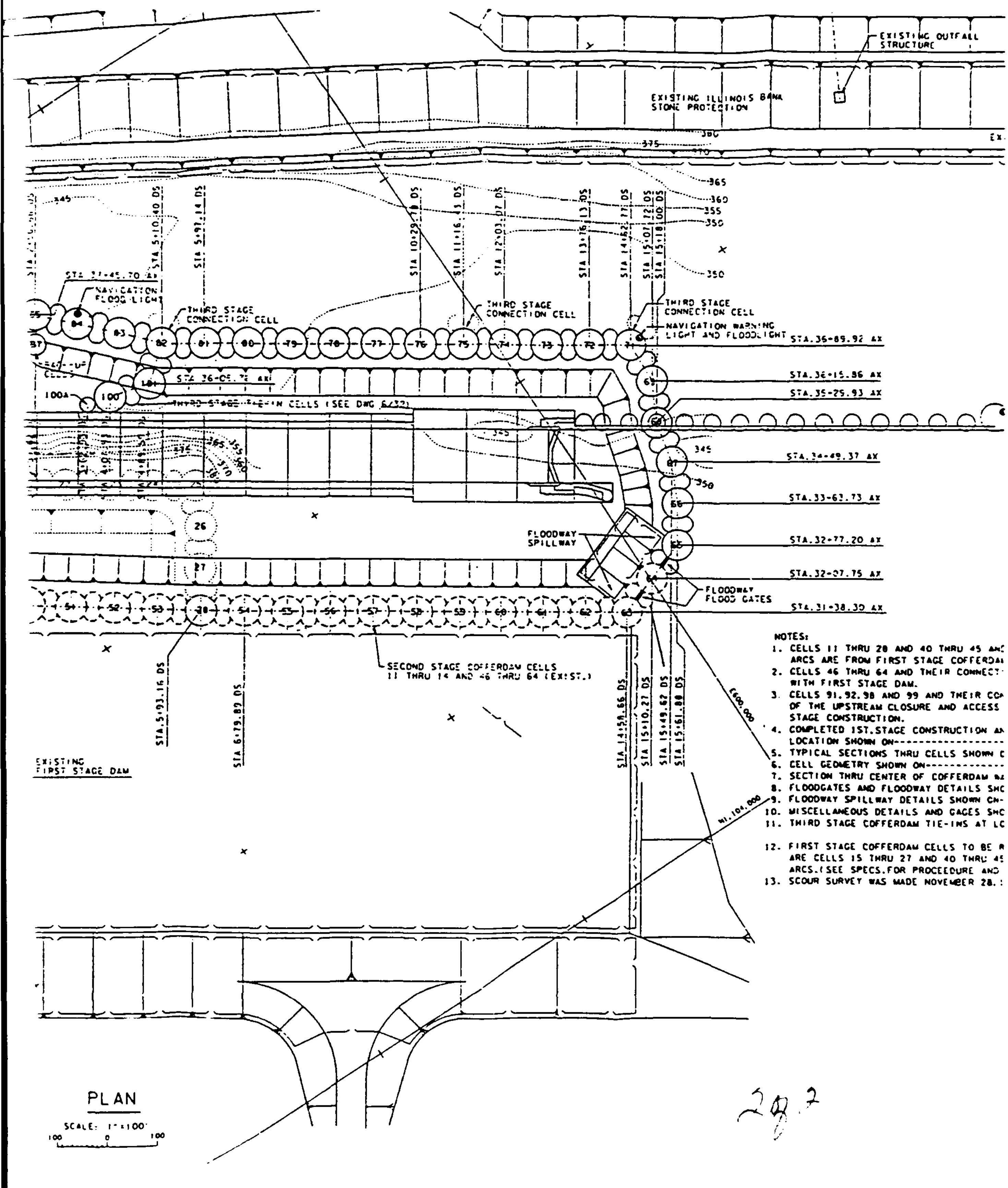




PLAN

SCALE: 1"=100'

FIG 4.2 STRUCTURAL FEATURES OF SECONDARY STAGE COFFERDAM



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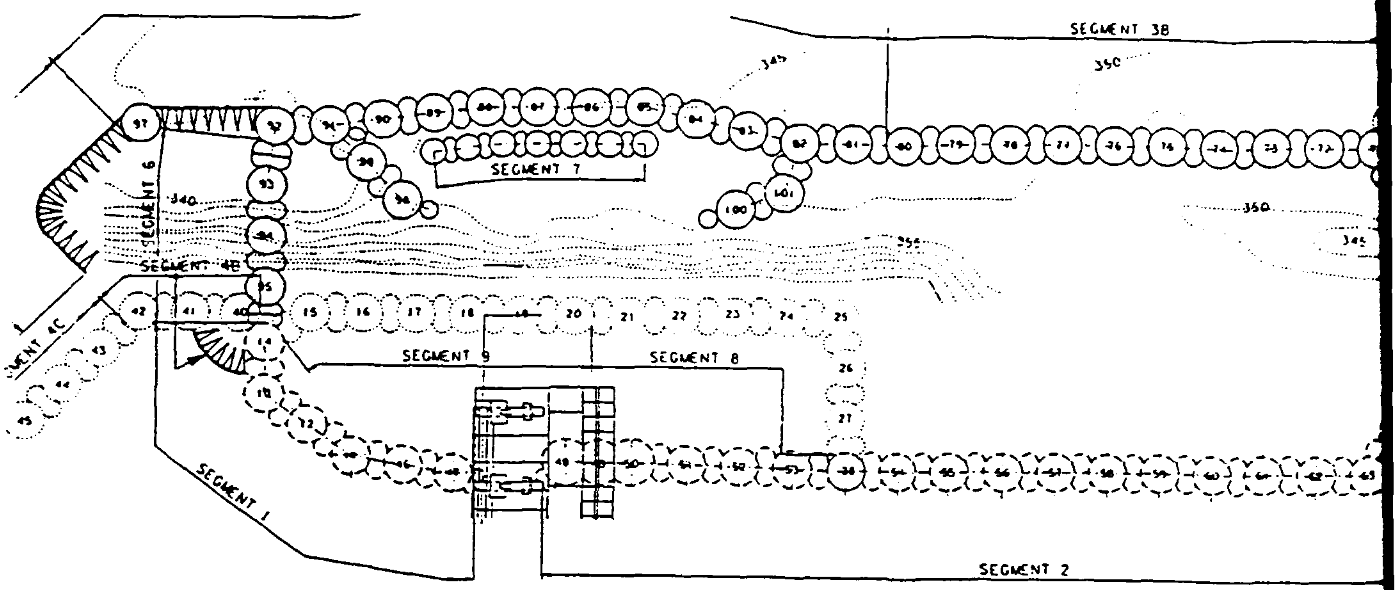

PLAN-SECOND STAGE COFFERDAM
(SHOWING CONSTRUCTION SEGMENT PLAN)
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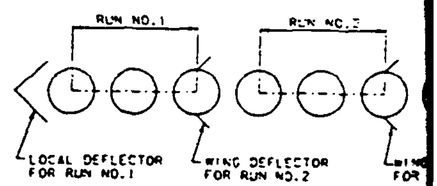

TYPICAL CELL CONSTRUCTION S
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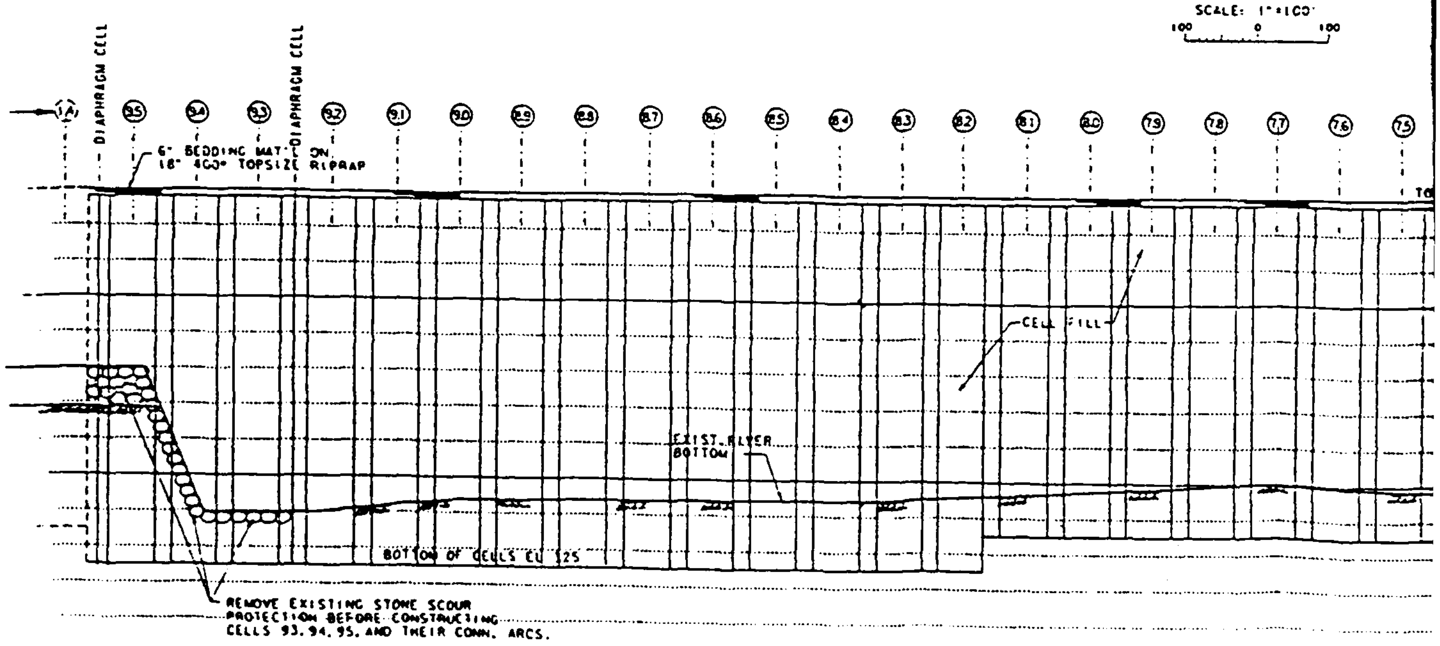
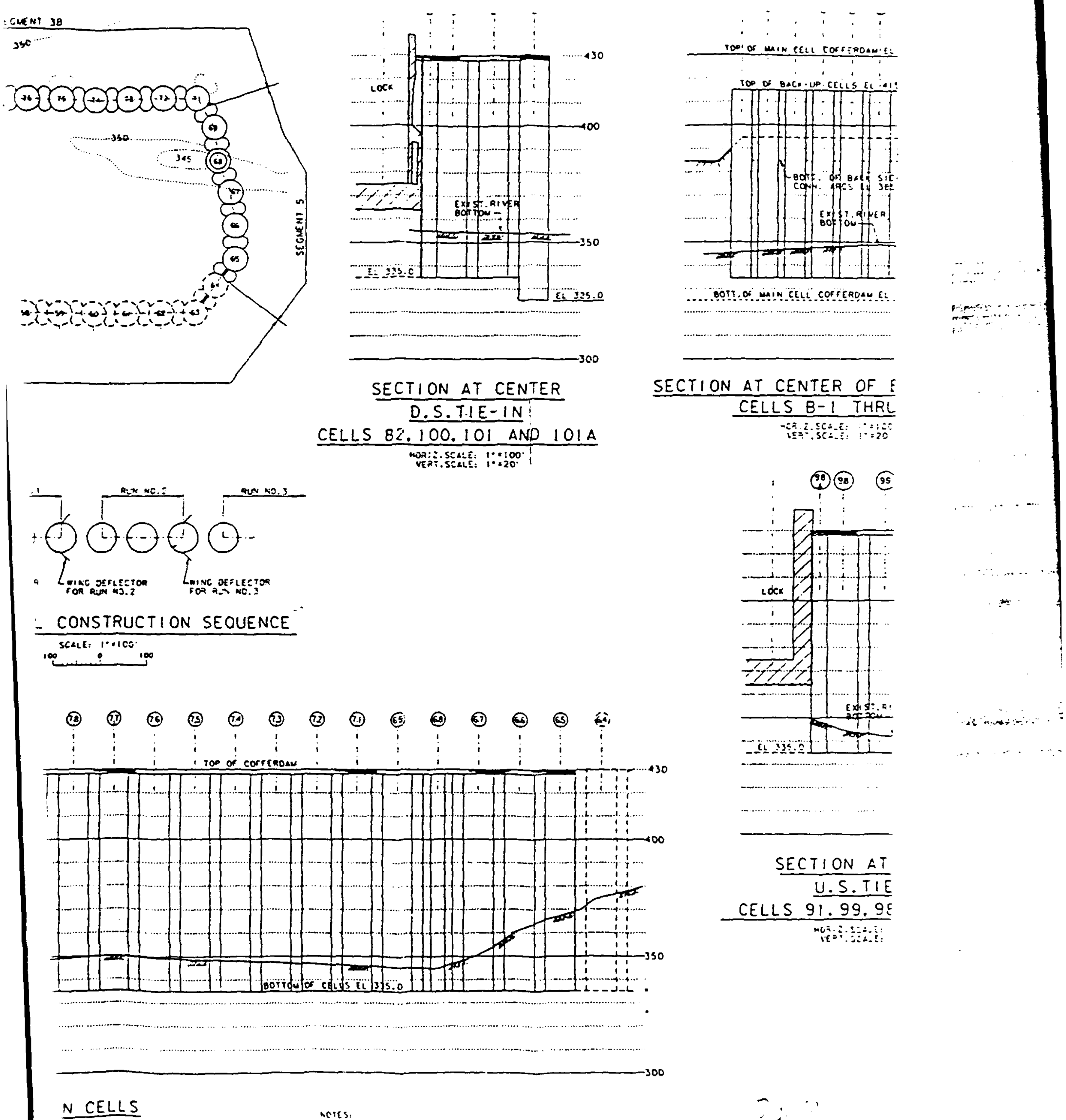
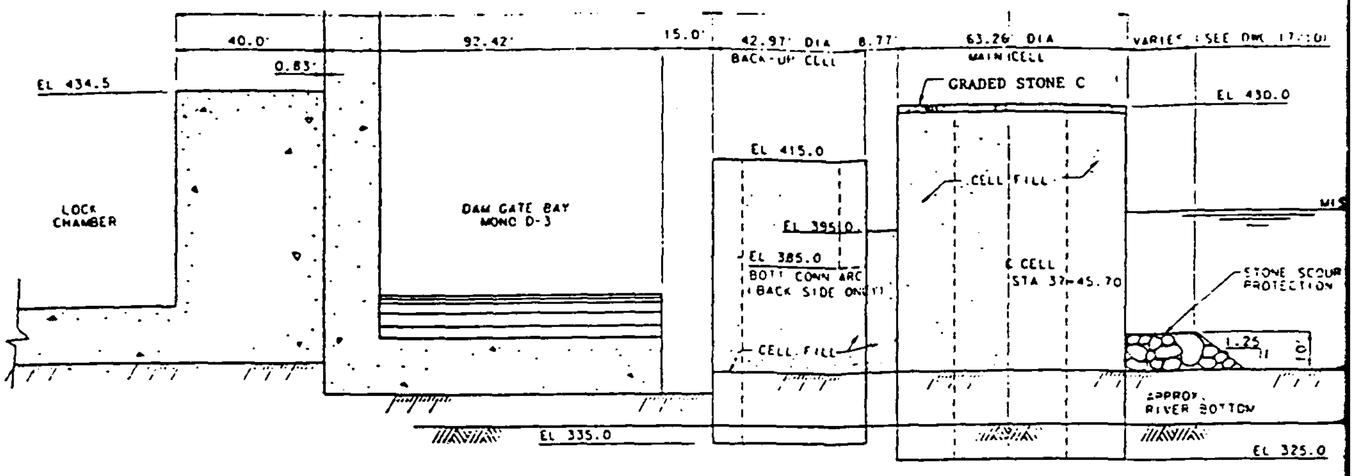


SECTION AT CENTER OF MAIN CELLS

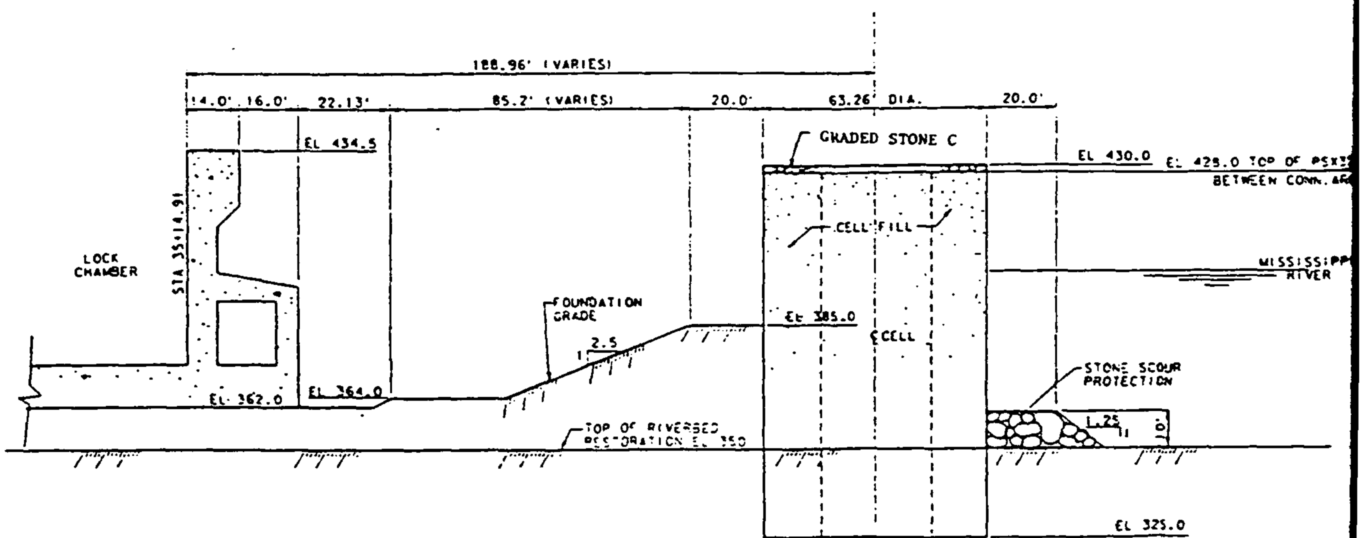
FIG 4.3 DETAILS OF REPRESENTATIVE CELL LAYOUTS





SECTION THRU CELL 87 ILLINOIS LEG

SCALE: 1" = 20'



SECTION THRU CELL 83 ILLINOIS LEG

SCALE: 1" = 20'

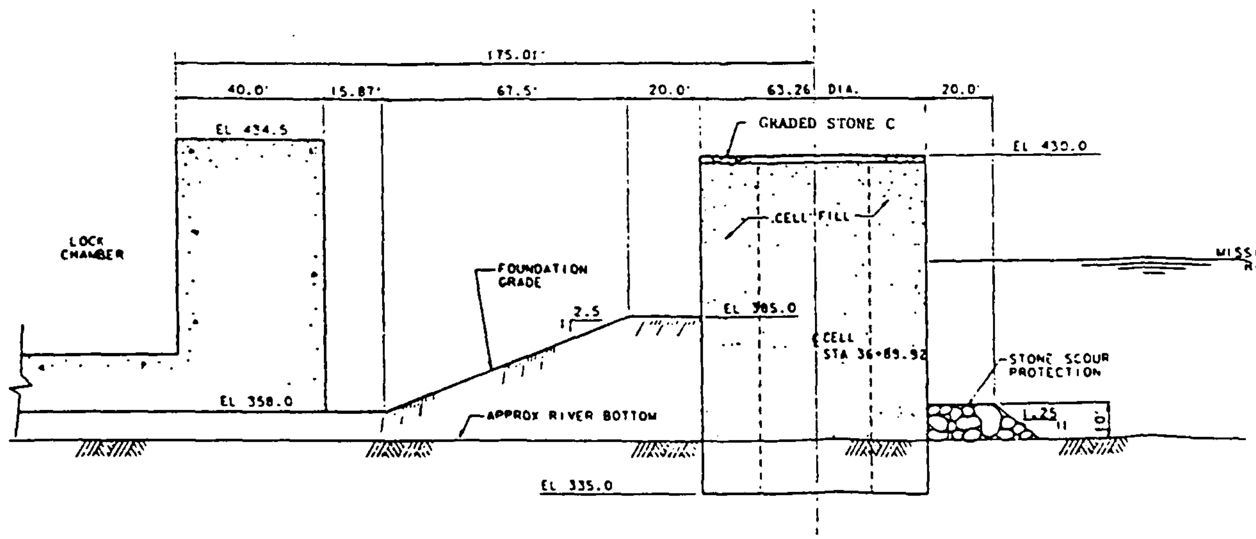
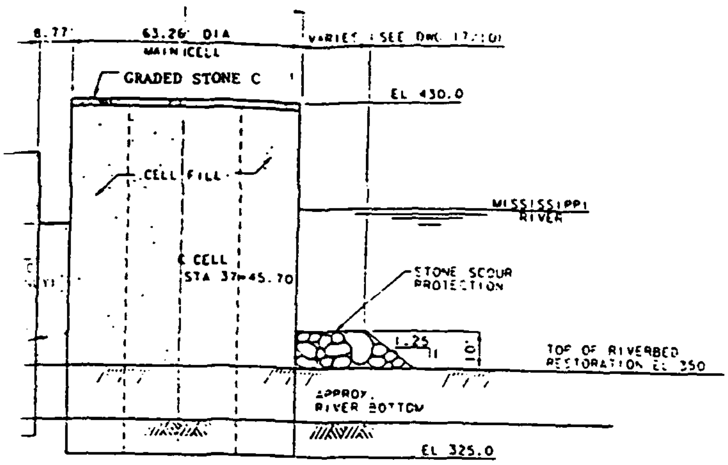
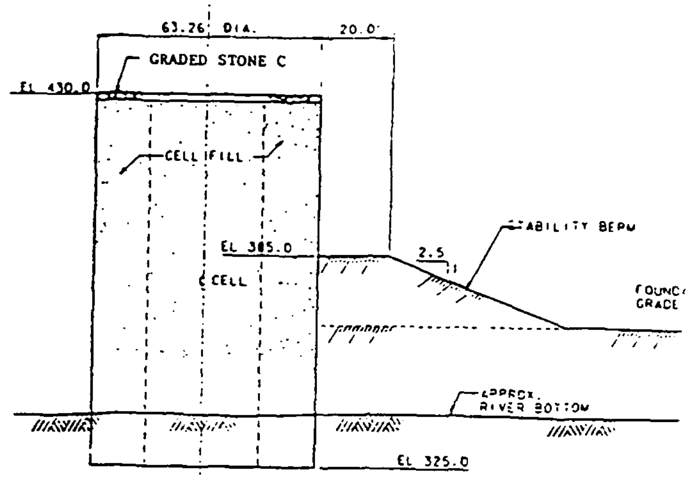


FIG 4.4 DETAILS OF REPRESENTATIVE CELL DESIGN PARAMETERS

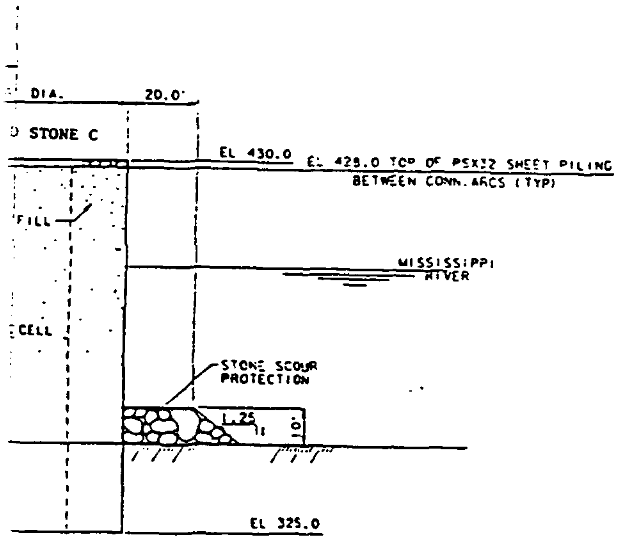


NOIS LEG

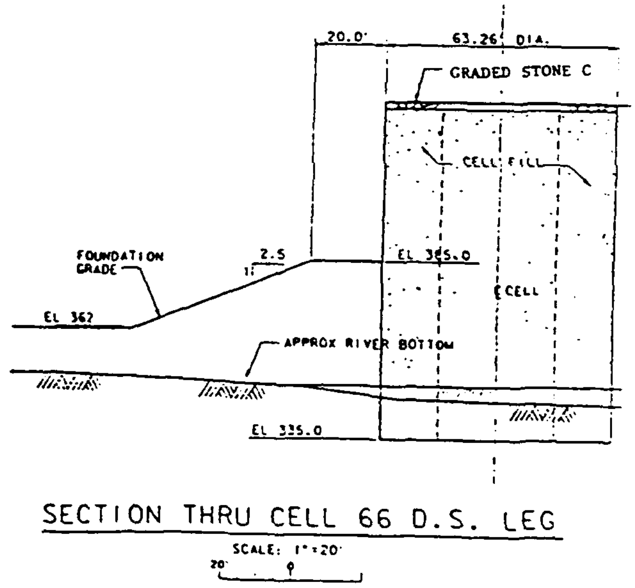


SECTION THRU CELL 94 U.S

SCALE: 1" = 20'

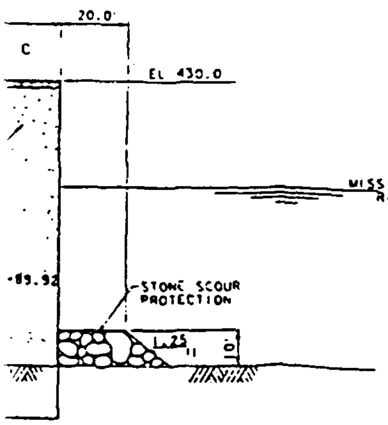


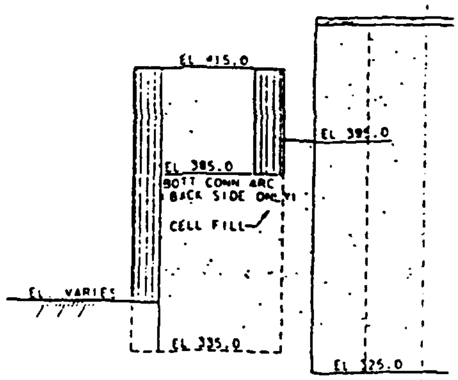
LEG



SECTION THRU CELL 66 D.S. LEG

SCALE: 1" = 20'





SECTION THRU BACKUP CELL CONN. ARCS

5.0 STUDY CHRONOLOGY

The Study began on March 1, 1986 utilizing a single channel AET 204GR acoustic emission recording unit. Monitoring continued with this unit until April 21, 1986. During this period the monitoring procedure consisted of alternating sequential 30-minute monitoring of AE counts and events at any one location. On April 21, 1986 dual unit monitoring utilizing an AET 204GR MIX/MUX 8 channel unit, in addition to the unit referred to above, was commenced. In this procedure counts were recorded for a 30-minute period on one unit as events from the same location were recorded on a second unit. This type of monitoring continued through July 2, 1986. Monitoring activity and the dates on which it occurred is shown on Figure 7.11. Initially all cells were monitored and the results reviewed to determine which cells displayed the most activity. Commencing in August 1986 only these more active "cells of interest" (68, 71, 80, 87, 91 and 92) were monitored.

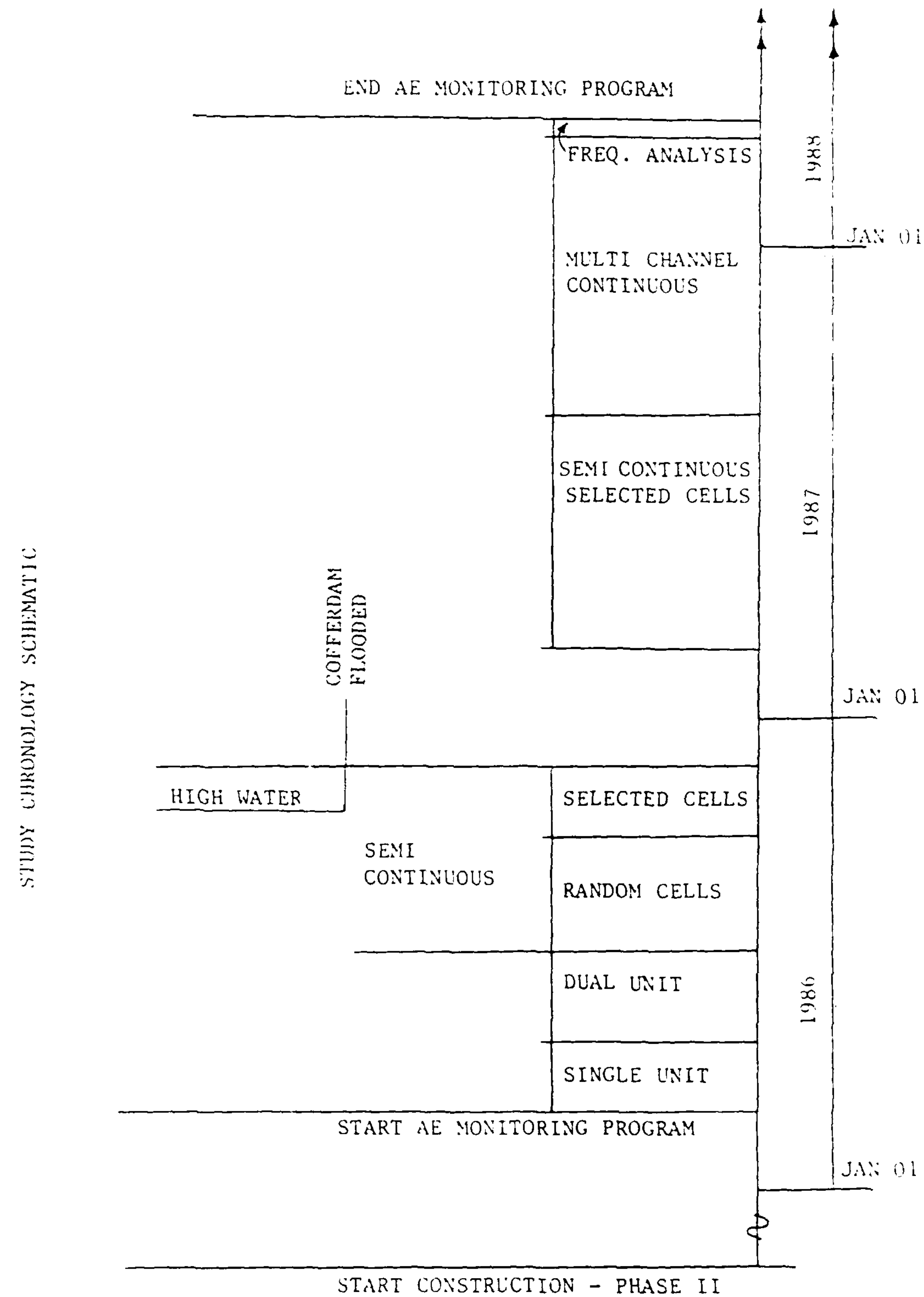
Semi-continuous monitoring was conducted from August 5, 1986 through September 30, 1986. This procedure consisted of recording counts only for two-hour periods at each cell of interest. From October 1, 1986 through November 24, 1986 monitoring consisted of recording counts for a 20-minute period per day on each of six selected cells. No further monitoring was conducted until February 24, 1987 at which time the 20-minute per day/six cell procedure was re-commenced and continued until August, 1987.

Both single and dual unit monitoring with the AET 204GR units produced output readings in sufficient number and quality

for analysis of cofferdam performance. However, the need for an equipment operator at all times during monitoring precluded obtaining a continuous record of AE activity. Such a continuous record would obviously provide more data of greater consistency and lead to more reliable analysis. Accordingly, in August, 1987 a PAC ATLAS 7016/3000 sixteen channel continuous monitoring unit was installed and all subsequent monitoring was conducted with this equipment until routine AE monitoring activity was suspended on March 25, 1988.

A special frequency and amplitude analysis was performed during the period from April 4 through 6, 1988 utilizing a Nicolet 4094 digital storage oscilloscope and associated equipment.

During the periods described above, the elevation of the Mississippi River was generally below 414 MSL NGVD. At these river levels AE activity was generally low to moderate. However, there were two significant periods of high water. The first occurred between May 15, and June 15, 1986 when the river elevation rose to a maximum of 421 MSL NGVD. The second flood period lasted from October 1, through November 7, 1986 at which time the river rose to Elev. 429.3 MSL NGVD. Since the cofferdam with top of sheet pile at El. 430 was in danger of being overtopped, a decision was made by the St. Louis District, Corps of Engineers to flood the cofferdam due to concern for its safety. A schematic diagram of the Study chronology is given in Figure 5.1. The data collected and the equipment and methods used during the periods described above will be presented and analyzed in subsequent Sections of this Report.



STUDY CHRONOLOGY SCHEMATIC	GROUND ENGINEERING, INC ST. LOUIS, MISSOURI
	MAH / JAD / 7-88 / Fig.

6.0 EQUIPMENT, INSTALLATION, PROCEDURE AND OPERATIONS

6.1 General:

As previously discussed, two separate types of AE monitoring equipment were utilized during the conduct of the Study. The first included both a single channel AET Model 204G unit and an eight channel AET Model 204GR MIX/MUX unit each manufactured by Acoustic Emission Technology Corporation of Sacramento, California. Each portable unit was battery-operated and was moved to various locations as tests of opportunity were conducted. The second was a sixteen channel PAC ATLAS 7016/3000 computerized system as manufactured by Physical Acoustics Corporation of Lawrenceville, New Jersey. It required 120-volt electrical service and was consequently operated from a fixed location.

In addition, a much more sophisticated system based on a Nicolet 4094 digital storage oscilloscope was used in the frequency and amplitude analysis conducted at the end of the monitoring program.

Each of these types is discussed more fully in the following paragraphs of this Section.

6.2 AET 204GR System

The Acoustic Emission Technology Corporation (AET) Model 204GR system is a complete battery-powered system designed to detect and process acoustic emissions from microseismic activity by measuring ringdown and event count summation, and ringdown with event count rate signal level.

The system contains integral signal amplification and filtering components and has a fixed or floating (automatic) threshold capability which augments the counting function. The floating threshold monitors the continuous system noise and adds a voltage proportional to the signal noise to the threshold voltage, resulting in a deadband which inhibits the counter from accumulating counts caused by varying background noise, as shown schematically in Fig. 6.3.

Selective use of the system's gain, scale, and rate options provides a means of assessing a wide range of acoustic activity.

6.2.1 Equipment Components

The single channel system is composed of three parts; a sensor, a preamplifier and the mainframe unit. They are interconnected with a six-foot cable from sensor to preamplifier and a 25-foot cable from preamplifier to mainframe. A twelve-volt battery pack supplies power to the unit and is connected to it with a two-foot cable. Both the mainframe and the battery pack are mounted in a substantial splash-proof portable steel container.

The eight-channel system has the same components as the single channel system plus a mixer/multiplex module. The MIX/MUX which is installed in the same enclosure as the mainframe enables AE data to be obtained from up to eight channels sequentially (multiplexing mode) or simultaneously (mixing mode). In the multiplex mode the signal from each channel is recorded and displayed sequentially. In the mix mode all signals are mixed together as they are recorded and the total number of signals is counted.

All sensors used with this equipment were 30 KHz resonant frequency and were attached to the sheet pile or other waveguide with a constant force clamp using a couplant gel. A 15 to 45 kHz bandpass filter was utilized to eliminate signals whose frequencies were outside of that range. Such a filter is required because sensor bandwidth is infinite, even though sensitivity decreases as signal frequency increases or decreases from the resonant frequency of the sensor. Each sensor is supplied with a calibration curve for use in evaluating its sensitivity.

The specifications of the components of the AET 204GR system are as shown in Table 6.1, AET 204GR System Component.

6.2.2 Data Collection and Reduction

6.2.2.1 Data Records

All data collected from observation of AE activity in any particular cell was transferred from field logs and stored on a computerized Data Record logsheet, an example is shown as Figure 6.1. This permanent record contains, in addition to 30 minutes of AE monitoring, information relating to instrumentation set-up, sensor placement, sensor type and environmental conditions at the time of test. An indication of extraneous activity occurring on or adjacent to the cell during the monitoring period (i.e., passing land and water traffic, local construction equipment operation, etc.) is also shown.

6.2.2.2 Data Recovery

Acoustic Emission parameters (counts/min and events/min) were obtained for diametrically opposite sides of a single

cylinderical sheetpile cell. Using sheetpiles as wave guides each side of the cell was monitored for 15 one-minute periods, i.e., 30 minutes total per cell. If the cell contained a wellpoint piezometer, an additional 30 minutes of monitoring was obtained for that cell using the steel standpipe piezometer as a waveguide for cell-fill material emissions. For such applications the cell number was designated /P (e.g., 92/P).

6.2.2.3 AE Data Reduction

For the majority of the data presented, the AE parameter selected to represent acoustical sensitivity was the ratio of counts/min and events/min, namely counts/events (C/E). The ratio C/E was tabulated on the Data Record for each test minute and for the total period monitored. Prior to commencement of dual unit monitoring, it was often the case that although a real-value for counts/min was recorded, it was also possible to obtain a 'zero' value for events/min (recorded at a subsequent time) and therefore instantaneous C/E was not available. In order to minimize the effect of this anomaly, counts/min and events/min recorded over a 30-minute period were summed and averaged to obtain a mean C/E (counts mean/events mean). In addition, the Data Record provides the mean values of counts/min and events/min for each 15 minute observation on each side of the cell and equivalent values for the (unbiased) standard deviations of these observations. These values, recorded in each Data Record, were utilized in subsequent analysis.

6.2.2.4 Dual Unit Monitoring

Dual unit monitoring permitted the monitoring of counts/min and events/min simultaneously using two AET 204GR units. As earlier readings and observations suggested, this arrangement was much preferred over the initial testing procedure with one AE unit in which counts/min were obtained for 15 one-minute intervals, followed by events/min for a similar period. Dual unit monitoring was initiated on April 21, 1986 and the documented results indicate this where appropriate.

In parallel with commencement of dual unit monitoring, a control procedure was introduced to 'calibrate' both AE units prior to each day's testing. These calibrations also played a role in subsequent data analysis since they were representative of the quality of data recovered during the monitoring of AE activity for that day. A typical Dual Unit Calibration is shown on Fig. 6.2.

6.2.2.5 Semi-Continuous Monitoring

Semi-continuous monitoring of selected cells was achieved by measuring AE counts/min for 2 hours per cell for each test day. The accumulated number of counts for each 15 minute period in the 2 hour test was recorded, and the counts/min subsequently computed.

6.2.2.6 Pencil Break Test

The pencil break test, conducted prior to each monitoring period, consisted of a simple reading of the AE counts/min registered by the equipment when a fixed length 0.5 mm pencil lead was forced to break while in contact with the sensor element.

This simple method not only ensured equipment functionability but also provided a 'crude', yet consistent, calibration for the system in-situ.

6.2.2.7 Threshold Voltage

The threshold voltage represents a limiting value of acoustic emissivity. Unless the AE signal is of sufficient strength (in terms of micro-voltage) an event will not be registered by the monitoring equipment. This limiting voltage may be fixed at some predetermined level or it may be floating, in which case the limit varies in accordance with changing background noise level. See Figure 6.3.

The number of ringdown counts is dependent upon the number of event signals which exceed the threshold voltage limit. The majority of AE monitoring conducted with the AET 204GR units has utilized the floating threshold technique to take into account the varying levels of background noise at the site.

6.2.2.8 Data Discrimination

For a variety of reasons, a small (0.2%) percentage of the data obtained was of poor quality or non-processable. This data has been rejected from subsequent analysis. It should be noted that most of this rejected data originates from the earlier single-unit monitoring.

The remaining (discriminated) data is normally annotated with a '[D]' suffix.

6.2.2.8.1 Criteria for Data Rejection

The principal reasons for data rejection of poor quality or

non-processable data were:

(a) Poor instrumentation calibration usually indicative of power supply voltage falling below an accepted minimum value.

(b) Relatively large (peak scale) emissivity, when associated with high levels of local site activity, e.g., piledrivers in full operations, barges docked (and often bumping) alongside or adjacent to the cell under test, and unusually high volume of contractor traffic on the cell during the testing period.

(c) Obvious instrumentation 'malfunction' such as 'low battery' warning light illuminating during a monitoring period.

6.2.2.9 Data Presentation

For the period from March through June 1986 each cell monitoring test was given a reference test number. For convenience it is this number which represents the 'time' basis against which the acoustic emission summaries and other parameters have been graphically presented. The reference test number closely reflects real-time (i.e. days from start of testing) although it ignores days or periods when no monitoring was conducted, and does not take into account consecutive test numbers (up to 5 or 6) on a single day of monitoring activity. For convenience, and where appropriate, actual dates have been included on the graphs. All data, including that for pile movements have been reduced to this

common time base and thus the interrelation of pertinent parameters may be studied conveniently.

For the period from July 1986 until the end of the Study, actual dates are used on all data presented.

In general, AE data monitored (counts/events) has been presented for individual main cofferdam cells and back-up cells. For convenience, some presentations represent a cell group, such as that for the Downstream Leg.

For semi-continuous monitoring the parameter counts/min is used for all AE presentations.

To ascertain the significance of the timing of the day-to-day monitoring, AE activity is also presented using a base of time-of-day.

Where appropriate, and in the interest of clarity, cell numbers are shown alongside their relevant data points.

6.3 PAC ATLAS 7016/3000 System

6.3.1 Hardware

The PAC ATLAS 7016/3000 continuous monitoring equipment consists of an Atlas 7016 16-Channel Industrial Acoustic Emission System and a 3000 Acoustic Emission Analyzer as supplied by Physical Acoustics Corporation (PAC). The system records acoustic emission counts and events and stores the data on standard floppy disks. The sixteen channels can record emissions monitored by sensors (transducers) remote to the central recording system but connected to it with standard RG58 coaxial cable utilizing BNC connectors. The distance from sensor to the

Atlas 7016/3000 unit may be as great as 750 feet without signal distortion. Both low and high frequency sensors were employed. The low frequency sensors had resonant frequencies of either 30 or 60 kHz. The 30 kHz sensor has an external preamplifier while the 60 kHz sensor (No. R6I) has an internal preamplifier. The high frequency sensor (No. R15I) has a resonant frequency of 150 kHz and is also furnished with an internal preamplifier. Bandpass filters of 20 to 100 kHz and 100 to 300 kHz, respectively, were installed when low or high frequency sensors were in use. The foregoing equipment is further described in Table 6.2. Each sensor has a calibration curve for evaluating its sensitivity.

6.3.2 Software

The Atlas 7016/3000 disk operating system is a version of CP/M 2.2 developed by PAC. It has all the standard attributes of a Z80 microprocessor-driven CP/M system but has been modified to read and write in a unique disk format. The data collection, replay and analysis program is entitled SUM/DAS. It is completely menu driven through a series of approximately 19 menus. These may be separated into four general categories; main menu, data collection menus, system and graph set-up menus and data retrieval menus. In data collection mode the system records and stores counts and events for periods of up to several days or more depending upon the test point interval selected from the System Parameters Menu. The Test Point Interval (TPI) is the time in seconds during which all events are summed and recorded. All data collected is stored on 5 1/4 inch floppy disks from which it can

be retrieved and replayed in either tabular or a variety of graphic formats. See Table 6.3, for a summary of available graphic output.

6.3.3 Monitoring Stations

Sixteen monitoring stations were established to fully utilize the sixteen channel capacity of the Atlas 7016/3000 system. Seven were located on the sheetpiles of circular cells or connecting arcs and nine at waveguides installed in the cell fill. The waveguides consist of three drill rods (AW) embedded at different locations in any one cell fill to depths of 30, 50 and 70 feet. It is recognized that a sheetpile is in itself a 100± foot long steel element which functions as a waveguide. However, for the purposes of this Study, the terms sheetpile and waveguide, as described above, will be used throughout. All stations were selected in the area between Cell 76 to Cell 80, based upon previous AE measurements and identification as an active area. The layout and location of all recording stations is shown in Figure 6.4. A descriptive designation, such as SP-76/77 or WG-76.50.N was assigned to each Monitoring Station. In this designation SP and WG stand for sheetpile and waveguide; 76 or 76/77 indicates cofferdam cell number or connecting arc on which the station is located; 30, 50 or 70 indicates waveguide depth and S,C or N denotes whether the waveguide is the south, central or north one in the cell.

At each station a sensor was mounted in close contact with either a sheetpile or a square plate welded to the top of the waveguide (drill rod). The sensor was secured to the sheetpile

with a clamp and contact was assured by the use of a couplant gel provided by PAC. The waveguide sensors were mounted in a vertical position and contact was maintained by a weight and the couplant gel. Both sheetpile and waveguide installations were protected from accidental damage by a protective housing. In the case of the sheetpile stations this was a standard electrical box, while the waveguides have a 8-inch diameter cast iron fill well cap and cover plate. Connection of the sensors to the Atlas 7016/3000 was effected by coaxial cable attached at each end with BNC connectors. The cable was run in conduit from the waveguides to the cell perimeter. From there all cables were supported from the cells and run to the Atlas 7016/3000 located on the connecting arc between cells 77 and 78.

6.3.4 Equipment Housing

When initially installed the Atlas 7016/3000 was installed in a 26X30X30 inch steel plate box with hinged doors front and back. The box was bolted to the top of the sheetpiles of connecting arc 77/78. This arrangement exposed the operator and equipment to the elements during data collection, set-up and retrieval. It also subjected the equipment to the prevailing adverse conditions of wind, dust and rain. After a brief period of operation under these conditions, it became apparent that this location and installation would not be satisfactory. Accordingly, the equipment was relocated into a trailer during the last half of October, 1987 and housed there till the end of monitoring.

6.3.5 Sensor Arrangement

The arrangement of the sensors and their associated recording channels is shown in Table 6.4. As indicated the initial installation consisted of 14 high frequency (150 kHz) sensors and one low frequency (30 kHz) sensor. These measured the emissions from seven sheetpile and seven waveguide stations. One waveguide (WG-77.50.C) was monitored by both a low (LF) and a high (HF) frequency sensor.

Two recording stations (WG-76.50.N and WG-79.70.N) were not in use due to physical difficulties. This configuration was continued until September 24, 1987, at which time a 60 kHz sensor was substituted for the 30 kHz sensor at WG-77.50.C. On November 3, 1987, two additional 60 kHz sensors were installed at WG-77.30.N and SP-77 thus providing three stations at which both an LF and a HF sensor were installed. In order to accomplish this within the sixteen channel capacity of the system, station SP-76 was deactivated. An analysis of events recorded at the same station by LF and HF sensors is discussed later in this Report.

On January 22, 1988 LF sensors were substituted for HF sensors at eleven monitoring stations and three locations were continued as HF stations. This configuration was continued until March 7, 1988 when a HF sensor was installed at WG-77.50.C in addition to the LF sensor at that location.

6.3.6 Procedure and Operations

As indicated above, the SUM/DAS software permits remote data acquisition and storage as well as subsequent retrieval and replay in a large number of different graphical presentations as

well as a standard tabular print of accumulated results. Either the graphical or tabular data can be retrieved for any desired time period during the data storage period.

6.3.6.1 Data Acquisition and Storage

Data acquisition is controlled by instructions selected from the System Parameters Menu, Figure 6.5. Items 4,5 and 7 of this Menu establish the Test Point Interval (TPI) and the active channels. The TPI is the time in seconds which will elapse between automatically generated test points. Once chosen for a given data collection set, emission data will be recorded at the TPI selected and cannnot be replayed at any other TPI. Item 5 establishes the channels which will actively receive data during the acquisition period. The specific channels are selected from a sub-menu and must have a properly mounted sensor and be appropriately connected to the Atlas 7016/3000. Item 7 determines whether a Test Point (TP) is generated on the channel which receives the first event only or on all channels upon the arrival of the first event. "All Arrivals" has been utilized throughout the data collected for this Report.

Upon initiation of data collection from Item 1 of the Main Menu, Figure 6.6 and subsequent sub-menus, the Atlas 7016/3000 commences recording and storage of events for a period of several days or more. As indicated previously, the data is stored on a floppy disk for subsequent replay and analysis. The software has the capability of real-time review of the data as collected, should that be desired. However, for the purposes of this Study,

storage and subsequent analysis was the desired method of operation.

6.3.6.2 Data Retrieval

The data collected and stored as described above may be retrieved and replayed in either tabular or graphical format. The tabular format is predetermined and may only be varied by the selection of different time periods for review. The data may be inspected graphically by channel or combination of channels, by counts, events, amplitude, and time. All retrieval is controlled by a series of menu driven commands.

6.3.6.2.1 Tabular Data Overview

Tabular data is obtained from the Main Menu, Figure 6.6, Item 7 and a series of sub-menus which permit selection of the time (in TPI) to be displayed and/or printed. Figure 6.9 and 6.10 are reports of data collected from Test Points 0 to 262 and 263 to 524 of the Data Set recorded from December 7 to December 11, 1987. In this Data Set the TPI is 250 seconds and the interval shown is 262 TP or 18:11:40 hours, minutes and seconds. Note that due to a "bug" in the software, high threshold (HT) Events should be shown as low threshold (LT) Events as changed on Figures 6.9 and 6.10. The frequency status of each of the sixteen channels is shown at the bottom of the data. As listed in Table 2.1 for this date channels 3,4 and 13 were collecting data from LF sensors. The total number of LT Events recorded during the time period of interest (TP 0 to 262) is shown on Figure 6.9 for channels 1 to 8 in the first line and channels 9

to 16 in the second. The total number of LF/LT Events is the sum of those for channels 3,4 and 13 or (5203+68+87) = 5358. Similarly the HF/HT Events are shown in the second set of totals for channels 1 to 8 and 9 to 16, respectively. The total for said Events for channels 1,2, 5-12 and 14-16 is (0+0+1+0+0+0+0+0+1+0+0+0+0) = 2. The Average/Channel values given are for all LF and HF channels, in that order. In the foregoing example the average events per channel are 5358/3 = 1786 and 2/13 = 0. The low and high frequency amplitude values are not for each channel but rather all Events in 5 dB increments, i.e., from 20 to 24 dB, 25 to 29 dB, 30 to 34 dB, etc. The average values cannot be derived from the data shown.

6.3.6.2.2 Graphical Data Overview

A large number of graphical presentations of the data collected and stored may be displayed and/or printed for further analysis. The possible graphic displays are shown below in Table 6.3.

The graphical display is established by selections from four menus and several sub-menus. The Main Menu, Figure 6.6, Item 6, permits selection of the total number of graphs to be displayed with a maximum of 15. Item 5 selects a Graph for which the parameters are to be established and Items 3 and 4 display the Y-Axis Menu, Figure 6.7, and the X-Axis Menu, Figure 6.8. Each of these menus in turn allows selection of parameter, channel, threshold, frequency, scale and type of graph. The Y-Axis Menu also permits selection of cumulative or non-cumulative plot. In the discussion of data collected which is presented later in this

Study, three types of graphs are displayed and analyzed. Typical graphs of these types are shown in Figures 6.11, Events vs. Channels, 6.12, Events vs Amplitude, and 6.13, Events vs Time.

Figure 6.11 is a typical presentation of all LT and HT and all LF and HF Events detected on each active channel for the time period in TPI shown. The dashed histogram bars indicate channels receiving LF emissions and the solid bars indicate HF. Where two bars are shown, the left is LT and the right HT Events. The two graphs shown on Figures 6.12 display amplitude distribution for LF and HF channels, respectively. Figure 6.13 is typical of the graph used in the primary analysis developed later in this Study. It is a display of non-cumulative LT Events experienced on a single channel for the time period shown in TPI. As previously indicated, the Y-Axis threshold label is reversed due to a "bug" in the software; therefore read LT for HT as changed on Figure 6.13. Other graphic displays are available and two are shown for general information in Figures 6.14, Counts vs. Events, and 6.15, Cumulative Events vs. Time. Figure 6.14 is generally considered to be an indication of the energy level of the emissions received. Figure 6.15 is a cumulative display of all LT Events recorded on all HF channels for the time period shown.

6.3.6.2.3 Data Retrieval Procedures

Data collected and stored on floppy disks is retrieved in the form described above by appropriate selections from the Main Menu, Figure 6.6, Items 7 and 8 and subsequent sub-menus. Item 7 initiates a sequence which produces the tabular data and Item 8 the graphical data described above.

As indicated previously, the Atlas 7016/3000 system was received in mid-August, 1987. A brief orientation period was conducted in the office and field. Field data collection commenced on or about September 1, 1987. During the period from September 1 to November 1, 1987, certain software difficulties were experienced. Upon initiation of data collection the system performed properly until TPI 200 was reached. At that point data collection stopped. This occurred repeatedly resulting in a number of Data Sets in which only 18:40 hours of data were stored. At several random times, however, data collection did continue for several days without interruption. This problem was discussed at length with PAC without resolution. PAC provided replacement Time Clock and CPU boards which were installed. However, the problem remained unsolved until early November at which time a different initiation procedure was utilized for data collection and the problem was solved. Since that time recording of AE emissions proceeded on schedule with four exceptions. Data sets for the periods November 20 to 23, 1987, November 30 to December 4, 1987, March 7 to 11, 1988; and March 11 to March 14, 1988 were each aborted after collection of 131, 242, 173 and 178 TP, respectively. In each case an error message was printed on the tabular data. Consultation with PAC in December 1987 suggested that a voltage incident could be responsible. An RFI/EMI voltage surge suppressor was subsequently installed. However, it does not provide protection against low voltage incidents. On March 11, 1988 a general power outage occurred during a data retrieval visit to the site. The power failure

produced an error message similar to that recorded as described above.

6.3.6.3 Pencil Break Calibration Test

Upon completion of the first data collection and storage phase on or about December 11, 1987, the high frequency (150 kHz) sensors were replaced by low frequency (60 kHz) sensors at all eight available waveguide stations and three sheetpile stations. Prior to this replacement, the LF (60 kHz) sensors were subjected to a pencil break calibration test. In this test all sensors were mounted in a circle on a six-inch diameter, 2-inch thick steel plate. Each was connected to one of the Atlas 7016/3000 channels with a ten-foot length of coaxial cable, appropriate LF boards installed and dip switches set. Two 100 second tests were conducted. During each test a 0.5 mm. pencil lead was broken at the center of the plate at ten second intervals. The events recorded at each channel were subsequently displayed in graphic form for later analysis.

6.4 Frequency Analysis

6.4.1 Equipment Configuration

The configuration of the system utilized in the frequency analysis of AE and other seismic signals recorded from the cofferdam structure is shown in Figure 6.16. Seismic waves were measured from sheetpiles or waveguides either by the PAC accelerometers (PAC direct signal output), or by the B&K 3484 accelerometer with B&K 2635 preamplifier, or both. Electric signals generated by each transducer in response to seismic waves

were monitored and recorded on floppy disks using a two-channel version of the Nicolet 4904 digital storage oscilloscope. Later, the records (up to 20) from each floppy disk were transferred from the Nicolet system data files to HP Vectra operated ILS (Interactive Laboratory System by Signal Technology, CA) data files. Data transfer conversion procedures were run using Henry, the data transfer software for Nicolet oscilloscopes. Graphic results of signal analysis were printed from the screen of the HP Vectra using an Epson MX 86e printer.

6.4.2 Procedures

Three types of tests were performed during the frequency analysis. These tests were as listed below:

(1) Determination of the frequency response characteristics of the PAC transducers as installed at sheetpile and waveguide monitoring stations.

(2) Determination of the attenuation characteristics of acoustic emissions across the sheetpile structure and through the joint between sheetpiles.

(3) Identification of various phenomena possibly responsible for the occurrence of microseismic events.

6.4.2.1 PAC Sensor Frequency Response

The PAC sensor response characteristics were tested using the break of a 0.5 mm pencil lead as a source of a wide band frequency impulse. Each pencil break was within two to five inches from the individual sensor under investigation.

The direction of impact was essentially parallel to the direction of the peak sensitivity of the sensor tested.

6.4.2.2 Attenuation Test Data

Attenuation tests were performed using BB shots aimed at sheetpiles on both sides of the SP-77 PAC sensor location. The target points were approximately 11.5 feet below the edge and close to the center of an individual sheetpile. The number of sheetpiles between the impact sheetpile and the sensor sheetpile was increased gradually to more than ten to develop an attenuation envelope.

6.4.2.3 Acoustic Emission Identification

Acoustic emissions generated by simultaneous phenomena as possible direct or indirect causes of event occurrence were monitored using B&K and the PAC sensors/accelerometers mounted side by side (five inches apart) on the same sheetpile at station SP-77. The PAC sensor was partially shielded from external elements by a rectangular steel enclosure attached to the sheetpile. The B&K transducer was not protected.

TABLE 6.1

AET 204GR SYSTEM COMPONENTS

Micro Processor:
AET 204GR MIX/MUX (8 channel) [Primary Unit]
AET 204G (1 channel) [Secondary Unit]

Sensor:
Model AC30L (Optimized for 30 kHz Frequencies)

Pre-Amplifier:
Model 140B (Bandpass Filter Range : 15-45 KHz)
(Operating Frequency Range : 15-45 KHz)

Cable:
Model 9110 Power/Signal Cable (varying length)

AET 204G EQUIPMENT SPECIFICATIONS

MODEL 204G MAINFRAME

AMPLIFIER:

System Gain	108 dB maximum (250,000 V/V), variable in 2 dB steps from 50 dB
Mainframe Gain	10dB (3.2 V/V) to 68dB (2,500V/V)
Mainframe Gain Accuracy	±.2 dB
Input Termination Impedance	51 Ohms
Square Wave Response	Clean, with little or no overshoot
Overdrive (15 V p-p) Recovery Time for error less than 1 volt:	
Lowest gain setting:	20 milliseconds
Highest gain setting:	150 milliseconds
Mainframe Noise	20mV (G) rms referred to AE output at highest gain setting
System Noise spectral density	2.5 nanovolts per root Hertz referred to preamp input

TABLE 6.1 (Cont'd.)

AE OUTPUT	
Voltage Range	16V p-p
Output Impedance	300 Ohms, single-ended
Bandwidth (from input to AE OUTPUT)	-1dB: 55Hz to 140kHz -3dB: 30Hz to 200kHz -6dB: 20Hz to 250kHz -20dB: 10Hz to 500kHz
COMPARATOR	
Threshold Fixed:	Adjustable from +0.25 to +7.0Vdc
Automatic:	Sums "Fixed" threshold voltage and 1.41 x "RMS" voltage, up to 7.0 volts maximum. Time Constant: 50 milliseconds
Hysteresis	Positive-going signal triggers at Vth negative-going signal at 0.1V
Maximum Count Rate	5X 10 counts per second
Count Range	1999 with selectable multipliers of 1,10,100,10 and 10
Bandwidth (Input through comparator, 1V RMS Signal)	30Hz to 200KHz (G)
EVENT OUTPUT	
Signal Characteristics	Goes from low (OV) to high (+5V) at first threshold crossing in an event; remains high for 1 milli-second after the last positive threshold crossing
Output Impedance:	4.7k Ohms
Max. Event Count Rate:	(B); 1000 events/sec. (G)
DISPLAY	3.5 digit LED

TABLE 6.1 (Cont'd.)

INTERNAL VOLTMETER	Measures threshold or "RMS" voltage and reads out on display. Resolution 10 mV, accuracy $\pm 2\%$
RECORDER OUTPUT	0.0025V x count shown in display. (0 to +4.998V). Output impedance 4.7k Ohms
"RMS" OUTPUT	
Bandwidth (input through RMS Output):	30Hz to 200kHZ
Time Constant	1.5 seconds
Output Drive	0 to +7Vdc
Output Impedance	4.7k Ohms
Calibration Voltage ("Full Scale"):	5.0 Volts
Calibration Method:	Time average of the absolute value of a sine wave
POWER SUPPLY	Internal 6.0 Ah gelled-electrolyte lead-acid battery or external +12 to +14 Vdc supply
Current Drain	Mainframe: 240 mA Mainframe plus 140 preamp (no signal): 260 mA Mainframe plus 140 preamp (overdriven): 450 mA
Operating Time @ 68 F (20 C)	4 hours
Recharge Time	8 hours
Low Battery Alarm	Activates at 11.1 Volts
PHYSICAL	
Dimensions (H x L x W)	14.5 x 13.5 x 8.0"(37 x 34 x 20 cm)
Weight	Approx. 20 pounds (9 kg)

TABLE 6.1 (Cont'd.)

ENVIRONMENTAL

Operating	0 to 95% relative humidity (non-condensing) 0 to 40 C (32 to 104 F)
Storage	0 to 100% relative humidity (non-condensing) -40 to +50 C (14 to 122 F)

MODEL 140B PRE-AMPLIFIER

Gain	40dB (x100)
Output Drive	8V p-p into 50 ohms @ 2MHz guaranteed, with ±12V power. Typically 17V p-p @ 175KHz with ±15 V power.
Dynamic Range	77dB minimum, 85dB typical. 0.125 to 2.0 MHz
Noise (Referred to input)	3.8 microvolts rms, typically 3.3 microvolts rms from 0.125MHz to 2.0MHz (2.4nV/Hz)
Overload Recovery Time	30 microseconds to +100mV, typically 20 microseconds
Input Impedance	Greater than 20K ohms in parallel with 30 pF, typically 23K ohms in paralle with 27 pF.
Output Impedance	Less than 4 ohms (calibrated into 50 ohms).
Common Mode Rejection	Greater than 40 dB
Input Protection	Internally self-limiting @ +1.4V
Power	±9Vdc to ± 20Vdc @ 20mA
Connectors	Input and output: Lemo RA0/302, RA1.304
Bandwidth	1.0 KHz to 2MHz
Temperature Stability	±0.5dB, -25 C to +100 C (-13 F to +212 F)

TABLE 6.1 (Cont'd.)

Dimensions	5-3/8" x 3-5/16" X 1-7/8" (13.6 x 8.4 x 4.8 cm)
Weight	9 ounces (0.26Kg)
Splash Resistant Enclosure: V & L	Dimensions: 6-7/8" x 3-3/16" x 2-1/16" (17.5 x 8.1 x 5.2 cm) Weight: 1 lb. 7 oz. (0.65Kg)

MODEL 204R MIXER/MULTIPLEXER

Bandwidth	X to 1 MHz
Channel Activity Threshold	Variable from 0 to 2Vdc
Number of Input Channels	Eight
Power	
Multiplexing mode	20mA plus preamplifier drain
Mixing mode	20mA plus drain of all mixed preamps
Multiplexer sampling rates	10, 30, and 60 seconds; 15, and 30 minutes

Note:
Bandwidth lower frequency (X) varies dependent upon multiplexor sampling rate.

TABLE 6.2

PAC ATLAS 7016/3000 EQUIPMENT SPECIFICATIONS

Mechanical:	
Height	22.2 cm. (8.75 in.)
Width	48.9 cm. (19.25 in.)
Depth	53.3 cm. (21.00 in.)
Electrical:	
Line Voltage	115 VAC +/- 10%
Line Frequency	60 Hz
AE Input:	
Voltage	28 VDC
Current	100 mA
Impedance	50 Ohm
Connector	BNC Single Ended
Filtering	20-100 KHz or (Interchangeable Modules) 100-300 KHz
3000 Interface:	
Impedance	50 Ohm
Connector	BNC Single Ended
Sensors:	
Resonant Freq.	R 6I = 60 KHz R15I = 150 KHz
Peak Sensitivity	, -30 dB (Ref. 1V/Bar)
Preamplifier Gain	40 dB
Noise	< 1.5 MV RMS
Operating Temp.	-45c to 75c
Dynamic Range	> 85 dB
Power Losses	< 3 dB for 750 ft. RG58 Cable

TABLE 6.3

ATLAS 7016/3000

SUM/DAS GRAPHS

Y-AXIS	X-AXIS							
	HTHFE	HTLFE	LTHFE	LTLFE	LFAMP	HFAMP	TIME	CHAN.
HTHFE	01-16	01-16	01-16	01-16	XXX	ALL	01-16	01-16
HTLFE	01-16	01-16	01-16	01-16	XXX	XXX	01-16	01-16
LTHFE	01-16	01-16	01-16	01-16	XXX	XXX	01-16	01-16
LTLFE	01-16	01-16	01-16	01-16	ALL	XXX	01-16	01-16
LFLTC	ALL	ALL	ALL	ALL	XXX	XXX	ALL	XXX
HFLTC	ALL	ALL	ALL	ALL	XXX	XXX	ALL	XXX

Notes:

1. 01-16 Indicates that any channel that meets frequency restrictions can be displayed graphically.
2. All Indicates all channels only. A single channel cannot be displayed graphically.
3. XXX Indicates not available. Cannot be displayed graphically.

TABLE 6.4

ATLAS 7016/3000

SENSOR LOCATION/DATE

1987-1988

STATION	08/23-09/24 CHAN.	FREQ.	09/24-11/03 CHAN.	FREQ.	11/03-12/11 CHAN.	FREQ.	01/22-03/07 CHAN.	FREQ.	03/07-03/25 CHAN.	FREQ.
WG-76.30.S	01	150	01	150	01	150	01	60	01	60
WG-76.70.C	02	150	02	150	02	150	02	60	02	60
WG-76.50.N	03	---	03	---	--	---	03	---	03	---
SP-76	04	150	04	150	--	---	04	60	04	60
SP-76/77	05	150	05	150	05	150	05	150	05	150
WG-77.70.S	06	150	06	150	06	150	06	60	06	60
WG-77.50.C	07	150	07	150	07	150	07	60	07	60
	13	30	13	60	13	60	13	---	13	150
WG-77.30.N	08	150	08	150	08	150	08	60	08	60
	--	---	--	---	04	60	--	---	--	---
SP-77	09	150	09	150	09	150	09	60	09	60
	--	---	--	---	03	60	--	---	--	---
SP-78/79	10	150	10	150	10	150	10	150	--	150
WG-79.50.S	11	150	11	150	11	150	11	60	11	60
WG-79.30.C	12	150	12	150	12	150	12	60	12	60
WG-79.70.N	--	---	--	---	--	---	--	---	--	---
SP-79	14	150	14	150	14	150	14	60	14	60
SP-79/80	15	150	15	150	15	150	15	60	15	60
SP-80	16	150	16	150	16	150	16	150	16	150

Notes: 1. --- indicates channel or monitoring station not in use.

2. From 01/22 to 03/11 channel 15 was operated with a 100-300 KHz instead of a 20-100 KHz band pass filter.

3. From 01/22 to 03/11 channel 16 was operated with a 20-100 KHz instead of a 100-300 KHz band pass filter.

ACOUSTIC EMISSION MONITORING
LOCK AND DAM 26 (REPLACEMENT)
PHASE II COFFERDAM PERFORMANCE

JOB# : 60799
RECORD#: 1
DATE : 03-Jun-86

TEST DATE :5/28/86 + CELL # : 85 + TIME : 1415

LOC ON CELL:3/9 SENS EL: ---
PIEZOMETER :N/A

CT RATE INT:60	GAIN (dB) : 96	WEATHER : CLEAR
THRESH VOLT:1.24	SCALE : 1	TEMP (F): 80
POOL ELEV :---	RIVER ELEV:	WIND : 0-5
PENCIL TEST:	SENS TYPE : 1756/1751	DIRECT'N: SE

REF# (MINS)	AE COUNTS PER MIN	AE EVENTS PER MIN	AE CTS/EVT	COMMENTS (B=Barge C=Crane T=Truck) COUNTS AND EVENTS
[A] 1	12	4	3.00	Tx2
2	10	2	5.00	
3	16	5	3.20	
4	5	2	2.50	T
5	7	3	2.33	
6	2	1	2.00	T
7	3	2	1.50	
8	2	2	1.00	
9	1	2	0.50	Tx2
10	5	1	5.00	
11	1	1	1.00	
12	16	6	2.67	
13	67	16	4.19	
14	21	11	1.91	
15	5	2	2.50	T
16	9	3	3.00	
[B] 17	13	6	2.17	
18	7	3	2.33	
19	10	3	3.33	
20	47	18	2.61	
21	52	16	3.25	Tx2
22	56	27	2.07	
23	21	11	1.91	
24	19	7	2.71	
25	15	5	3.00	
26	6	2	3.00	
27	7	3	2.33	T
28	9	3	3.00	
29	11	3	3.67	
30	15	5	3.00	

	(C/M)	(E/M)	(C/E)	GENERAL NOTES
MEAN [A]	11.53	4.00	2.55	
MEAN [B]	19.80	7.67	2.76	
MEAN [A&B]	15.67	5.83	2.66	
SD/U [A]	16.55	4.23	1.37	
SD/U [B]	17.13	7.28	0.51	
SD/U [A&B]	17.07	6.14	1.02	

C/M (MEAN)/E/M (MEAN), [A&B] = 2.69 :5.28/86 85 :FILESPEC

GROUND ENGINEERING INC. ST LOUIS, MISSOURI

FIG 6.1 AET 204GR TYPICAL DATA RECORD

P	B	B Est
23	18	17.972
19	16	15.054
14	10	11.407
7	7	6.301
8	7	7.031
7	6	6.301
5	5	4.842
6	7	5.572
6	6	5.572
3	4	3.383
2	1	2.654
5	3	4.842
2	3	2.654
8	6	7.031
3	5	3.383

Regression Output:

Constant		1.195085
Std Err of Y Est		1.109695
R Squared		0.946447
No. of Observations		15
Degrees of Freedom		13
X Coefficient(s)	0.729438	
Std Err of Coef.	0.048123	

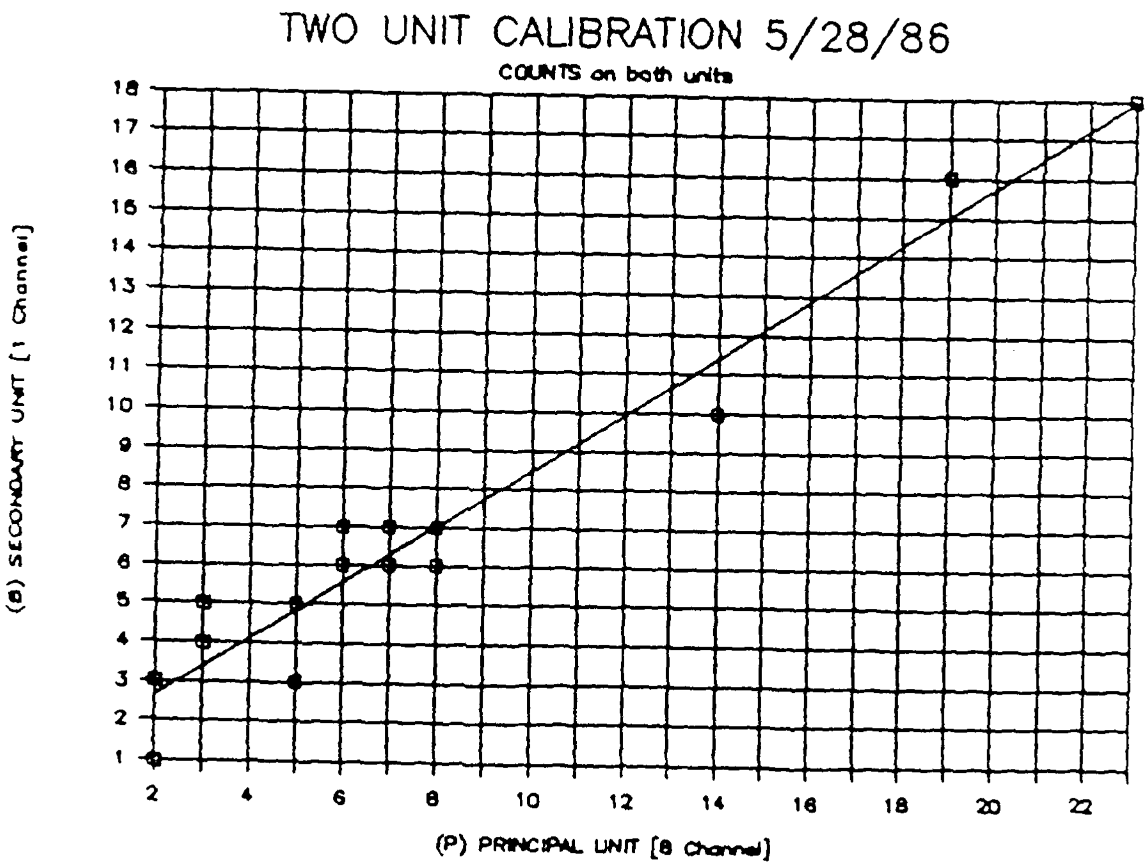


FIG 6.2 AET 204GR TYPICAL DUAL UNIT CALIBRATION

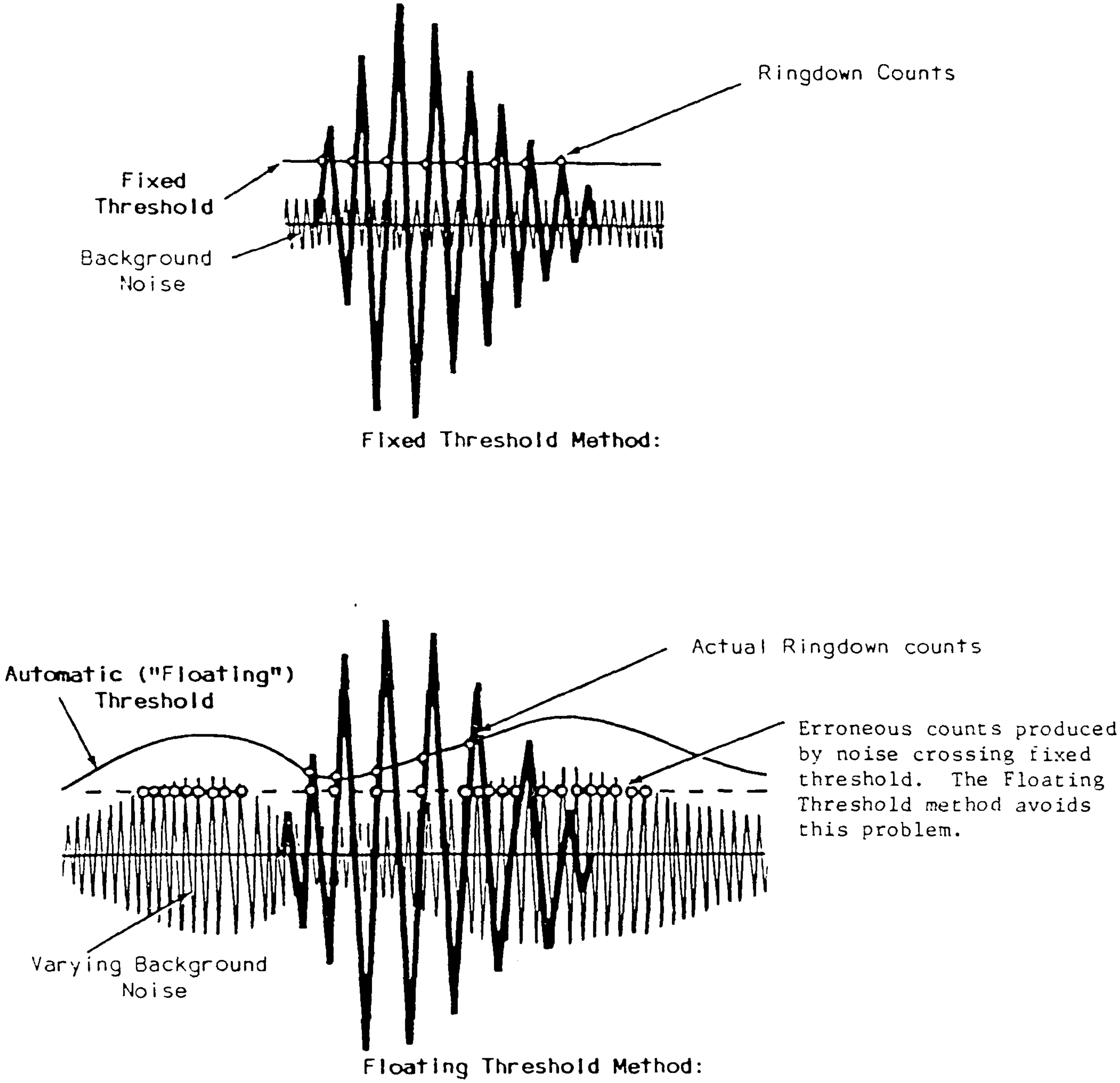
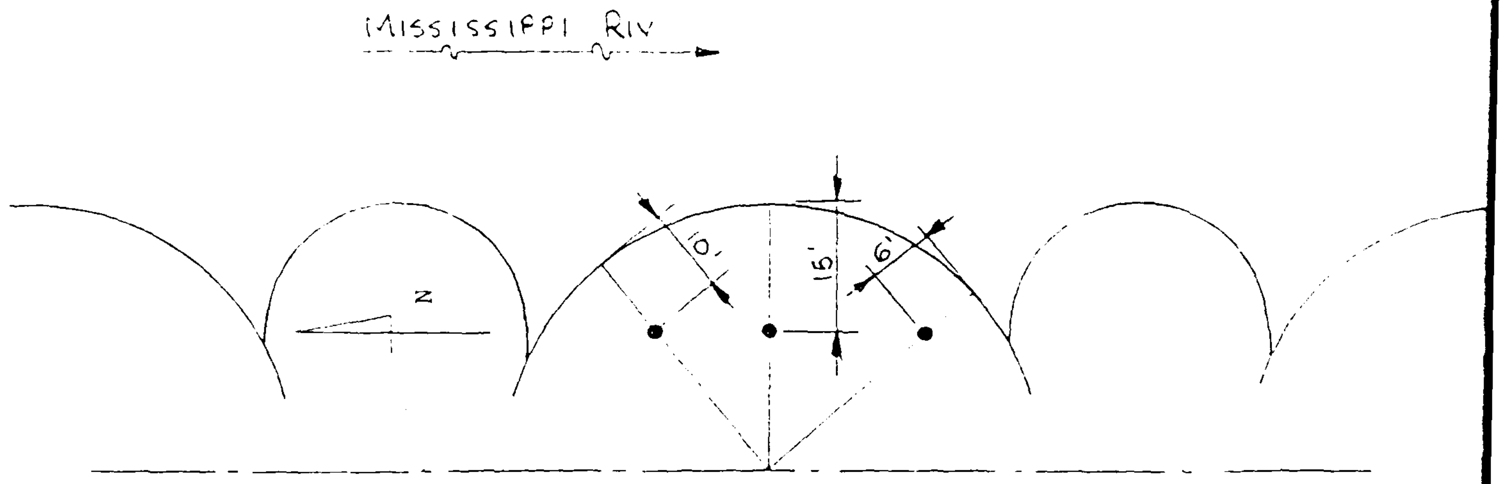
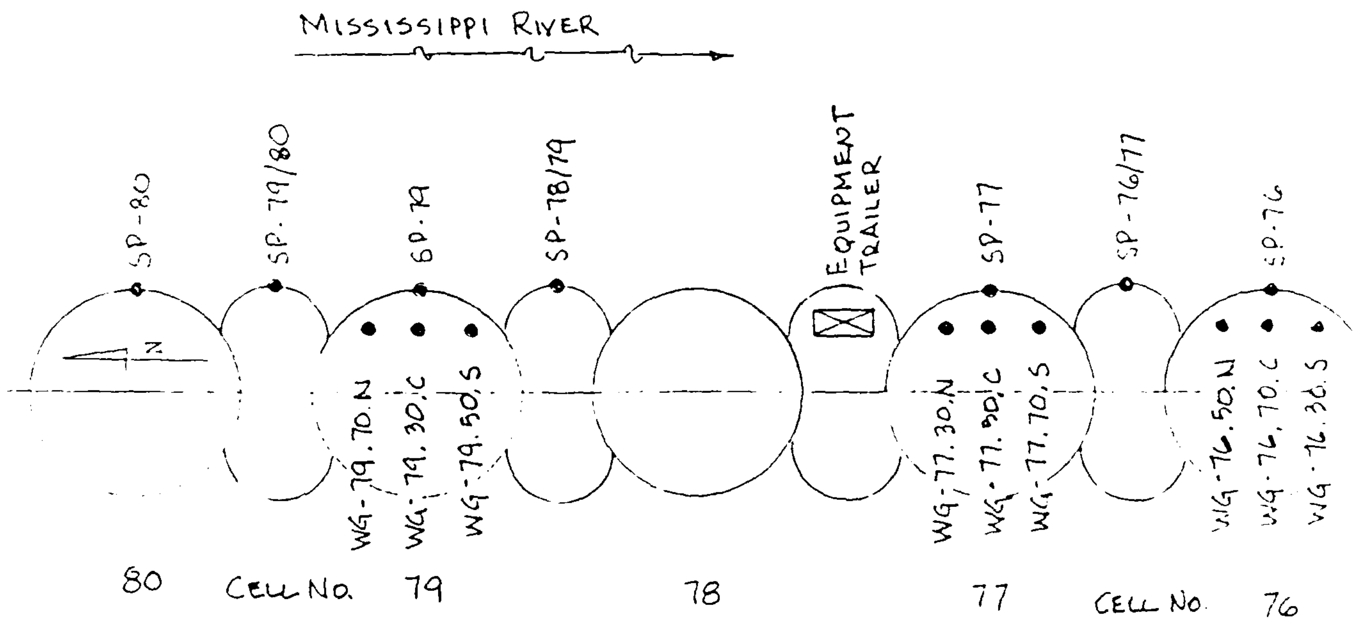


FIG 5.3 AET 204GR COMPARISON OF FIXED & FLOATING THRESHOLD



NO SCALE

WAVEGUIDE LAYOUT



NO SCALE

FIG 6.4 ATLAS 7016/3000 MONITORING STATION LOCATION

```
  A-Dump is OFF          DATA ACQUISITION SOFTWARE          05/20/88 08:43:51
>  1: Cancel scroll           13: Enter Test Label
   2: Read graph setup        14: Change from MANUAL DUMP
   3: Write graph setup
   4: Change test point interval (sec.) from 1
   5: Change active channel(s) from
   6: Change DEAD TIME (ms.) from 10
   7: Change EVENT data from FIRST arrivals
   8: Change Tabular Dump from NON-Cumulative
   9: Change Tabular Dump from ALL DATA
  10: Change Load Cell scaling from +/-  1000 Lbs. F.S.
  11: Change Alarm setup
  12: Change Filter setup
```

FIG 6.5 ATLAS 7016/3000 SYSTEMS PARAMETERS MENU

```
A-Dump is OFF          DATA ACQUISITION SOFTWARE          05/20/88 08:44:39
                 >  1: Do Data Collection
                    2: Set SYSTEM PARAMETERS
                    3: Set Y axis PARAMETERS
                    4: Set X axis PARAMETERS
                    5: Change CURRENT graph from 1
                    6: Change NUMBER of graphs from 5
                    7: Goto DUMP menu
                    8: Goto REPLAY menu
                    9: Change Replay rate from 1
                   10: Change Graph display from ALL DATA
                   11: EXIT to Disk Operating System
```

FIG 6.6 ATLAS 7016/3000 MAIN MENU

```
A-Dump is OFF          DATA ACQUISITION SOFTWARE          05/20/88 08:45:10
>  1: Cancel Scroll          13: Change from LINEAR SCALE
   2: Change Y parameter from Events
   3: Change Y channel from
   4: Change Y Threshold from Lo
   5: Change Y Frequency from Lo
   6: Change from AUTO SCALE
   7: Change Y minimum from  0
   8: Change Y maximum from  50
   9: Change Y Multiplier from 1
  10: Change from INTERVAL SUM
  11: Change from HISTOGRAM
  12: Change from NON-CUMULATIVE
```

FIG 6.7 ATLAS 7016/3000 Y-AXIS MENU

```
A-Dump is OFF          DATA ACQUISITION SOFTWARE          05/20/88 08:45:42

                  >  1: Cancel Scroll
                     2: Change X parameter from Time (Sec)
                     3: Change X channel from
                     4: Change X Threshold from Lo
                     5: Change X Frequency from Lo
                     6: Change X minimum from 0
                     7: Change X maximum from 1000
                     8: Change X multiplier from 1
                     9: Change from LINEAR SCALE
                    10: Change INTERVAL from 1
```

FIG 6.8 ATLAS 7016/3000 X-AXIS MENU

```
A-ARV   A-Dump is ON                        12/07/87 12:08                          07/09/88 09:51:26
          Test Point #   Ø - 262            (Time)                       FRP #     1
          Time of Test Point                Start    00 00:00:00         Finish  00 18:11:40
          Parametric input                  Start            00          Finish          00

          Cumulative Data for Test - All Hits
Low F/LT      Events              5358       Low Freq.  Counts                  47884
High F/HT     Events                02       High Freq. Counts                  78970

Low   Thres. Evnts (1-8) (9-16)   Ave. / Ch.  =      1786        417
        01         64      5203      68      1036       85         14          12
       514       1094        16      13        87     1078        567         937
High Thres. Evnts (1-8) (9-16)    Ave. / Ch.  =        00         00
        00         00        01      01        01   [illegible]   00          00
        00         00        01      00        00   [illegible]   00          00
Low Freq. Amp.(20-59 dB) (60-99 dB) Ave./Pt. =        45.
        00        454       361     750       966      864        765         567
       254         63        06      00        00       00         00          00
High Freq. Amp.(20-59 dB) (60-99 dB) Ave./Pt.=        44.4
        00        525       363     700      1017     1344        707         297
       165         95        35      06        01       00         01          01

Channel Status H H L L H H H H H H H H L H H H
```

FIG 6.9 ATLAS 7016/3000 TYPICAL TABULAR DATA;

TEST POINTS 0-262

```
A-ARV   A-Dump is ON               12/07/87 12:08                         07/09/88 10:03:00
          Test Point # 262- 524     (Time)                     FRP #     1
          Time of Test Point        Start     00 00:00:00      Finish   01 12:23:20
          Parametric input          Start            00        Finish          00

          Cumulative Data for Test - All Hits

Low F/LT     Events              5098     Low Freq.  Counts              46777
High F/HT    Events                51     High Freq. Counts             298399

Low   Thres. Evnts (1-8) (9-16)   Ave. / Ch.  =      1699     1072
        03        18      4933      84      3696       41       23        24
      1123      1793        10      21        81     2663     2092      2434
High Thres. Evnts (1-8) (9-16)   Ave. / Ch.  =        04       03
        00        00        11      01        22       00       00        00
        03        04        00      00        01       11       03        08
Low Freq. Amp.(20-59 dB) (60-99 dB) Ave./Pt. =      44.9
        00       385       349     671       767      724      624       532
       206        35        06      02        01       00       00        00
High Freq. Amp.(20-59 dB) (60-99 dB) Ave./Pt.=      43.4
        00      1164      1369    2350      2667     3046     1471       761
       344       176        62      10        05       02       01        00

Channel Status H H L L H H H H H H H H L H H H
```

FIG 6.10 ATLAS 7016/3000 TYPICAL TABULAR DATA;

TEST POINTS 262-524

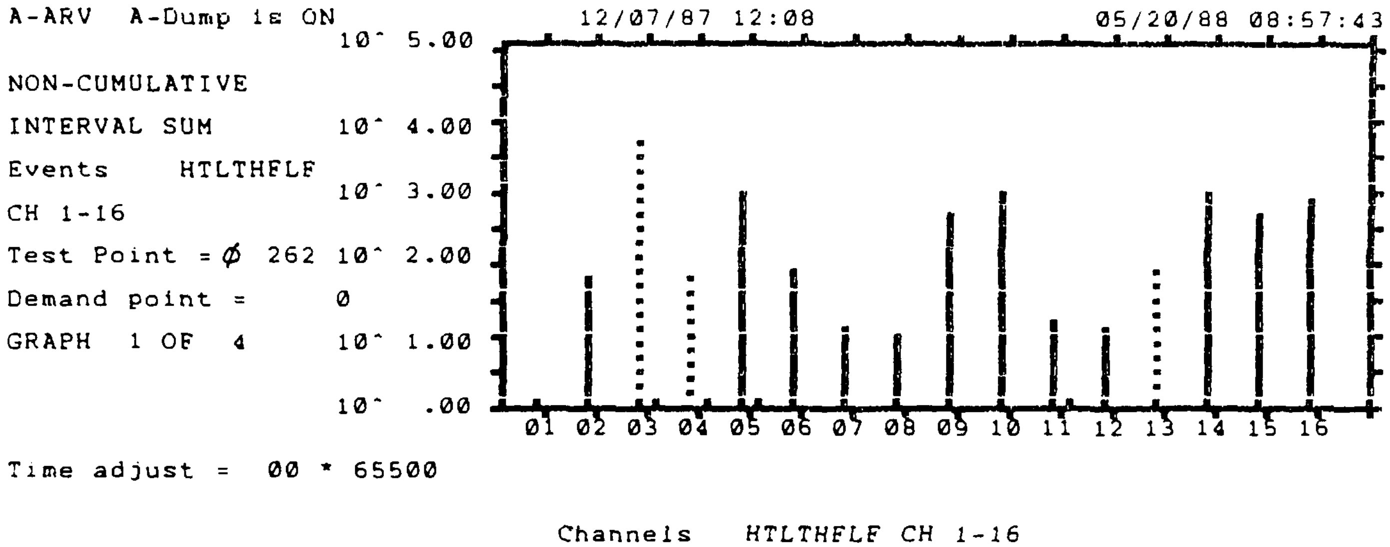


FIG 6.11 ATLAS 7016/3000

TYPICAL GRAPH OF EVENTS VS CHANNELS

A-ARV A-Dump is ON

NON-CUMULATIVE

INTERVAL SUM

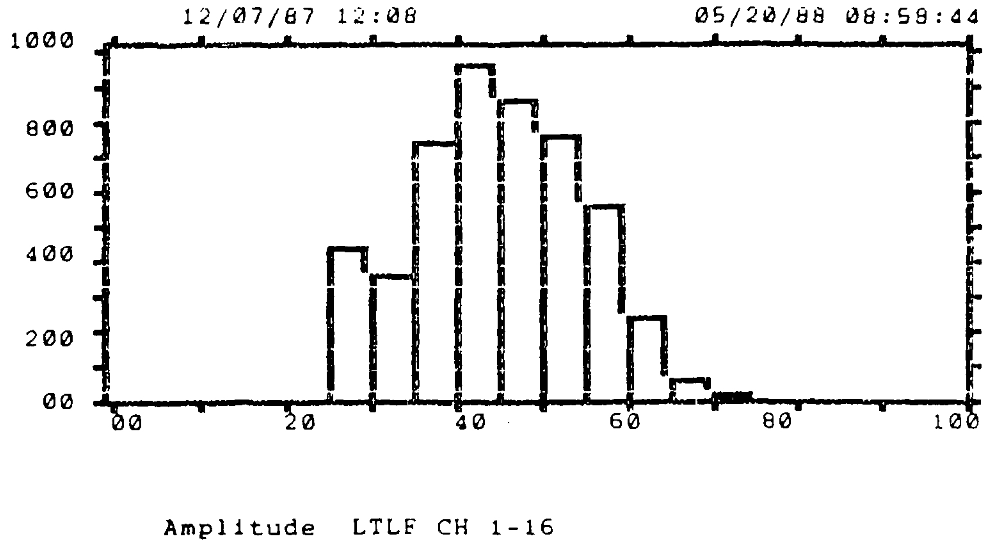
Events LTLF

CH 3,4,13

Test Point = Ø-262

Demand point = 0

GRAPH 2 OF 4



A-ARV A-Dump is ON

NON-CUMULATIVE

INTERVAL SUM

Events LTHF

CH 1,2,5-12,14-16

Test Point = Ø-262

Demand point = 0

GRAPH 3 OF 4

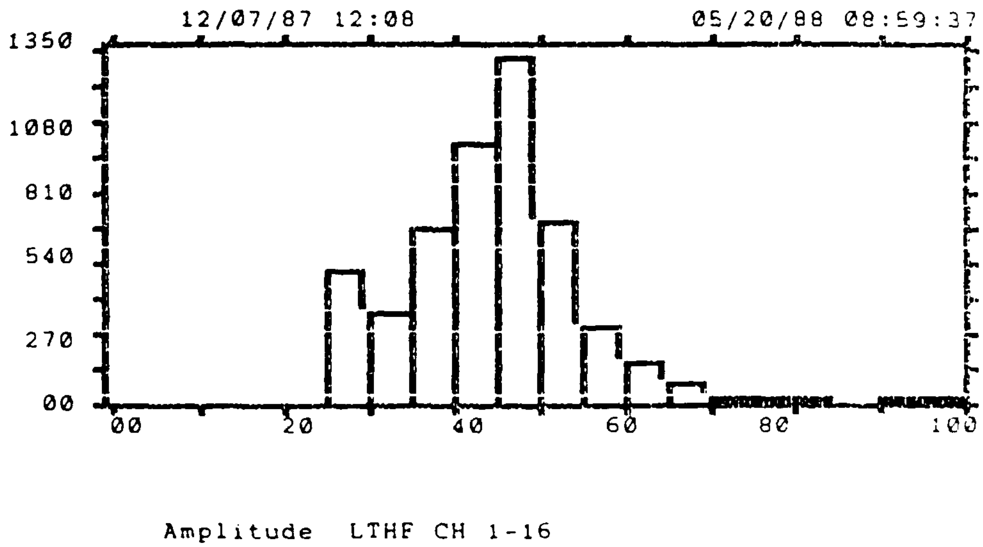


FIG 6.12 ATLAS 7016/3000

TYPICAL GRAPH OF EVENTS VS AMPLITUDE

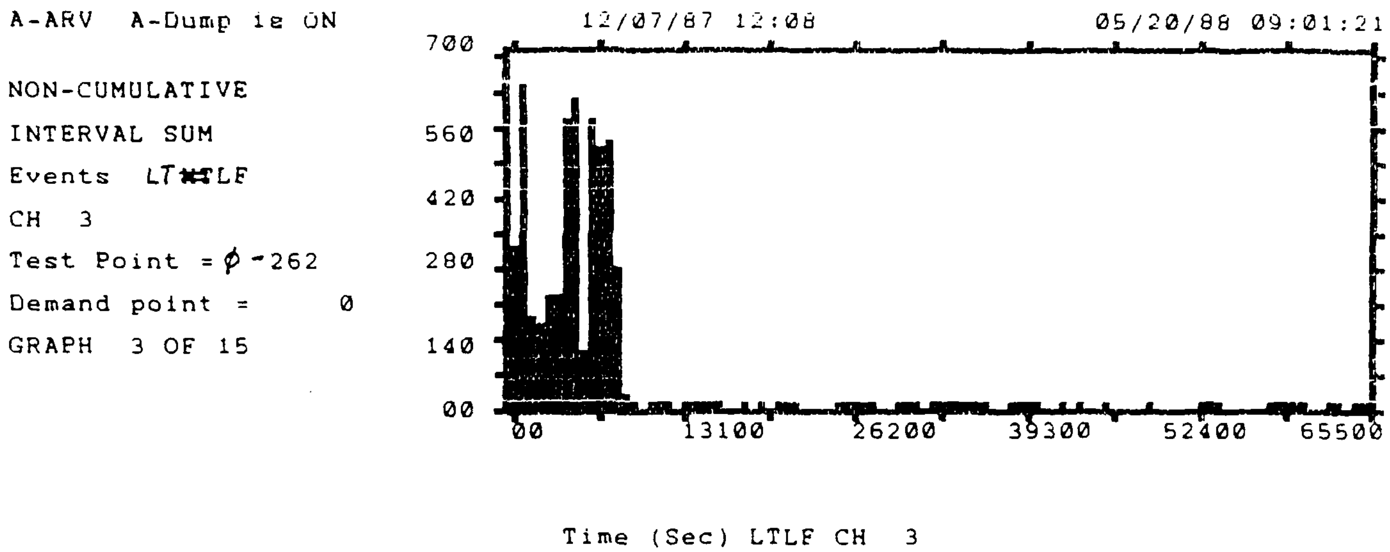


FIG 6.13 ATLAS 7016/3000

TYPICAL GRAPH OF EVENTS VS TIME

A-ARV A-Dump is ON

NON-CUMULATIVE

INTERVAL SUM

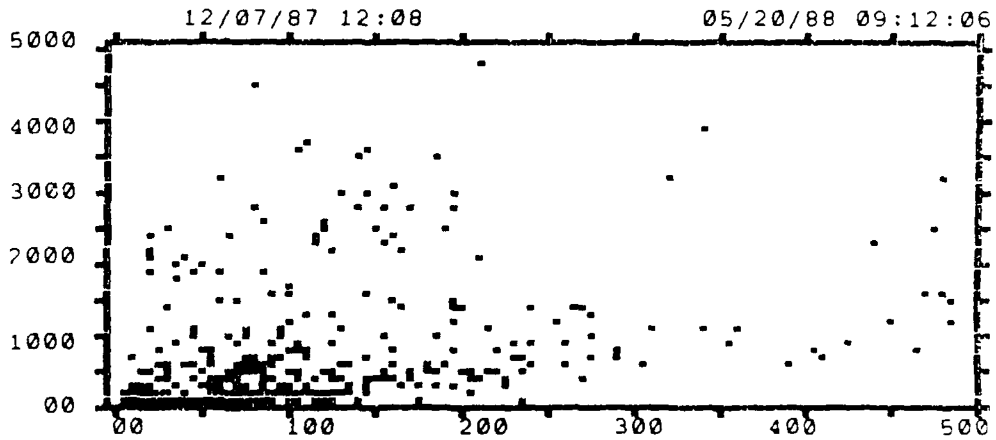
Counts   LTHF

CH 1,2,5-12,14-16

Test Point = ϕ-842

Demand point =   0

GRAPH 13 OF 15



Events   LTHF CH 1,2,5-12,14-16

FIG 6.14 ATLAS 7016/3000

TYPICAL GRAPH OF COUNTS VS EVENTS

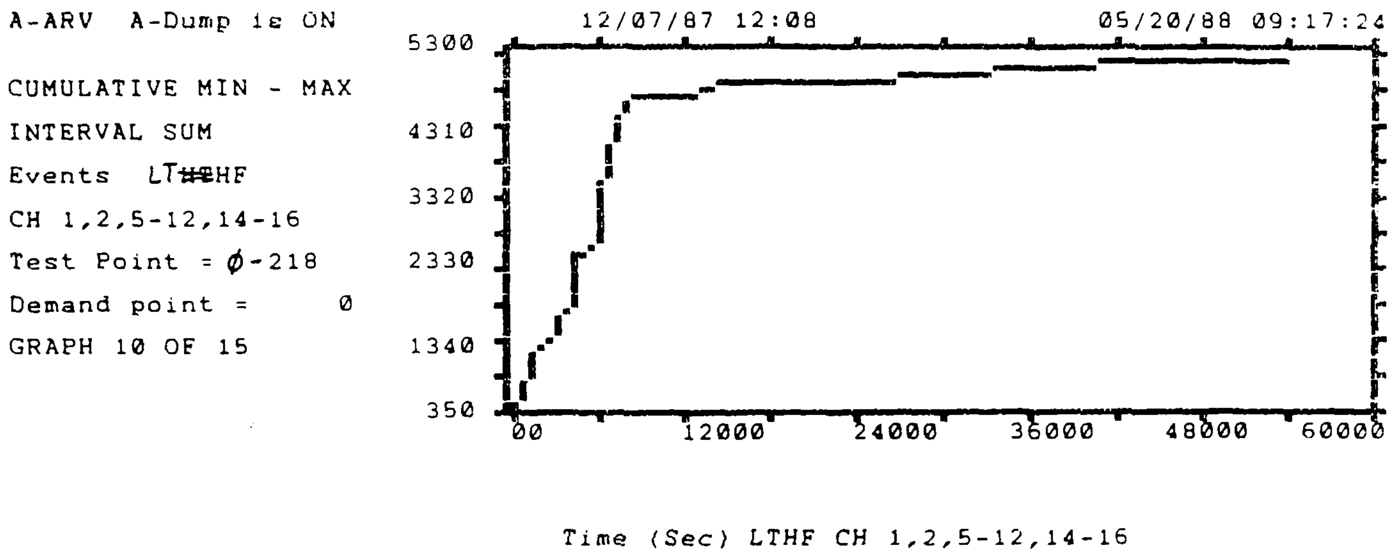
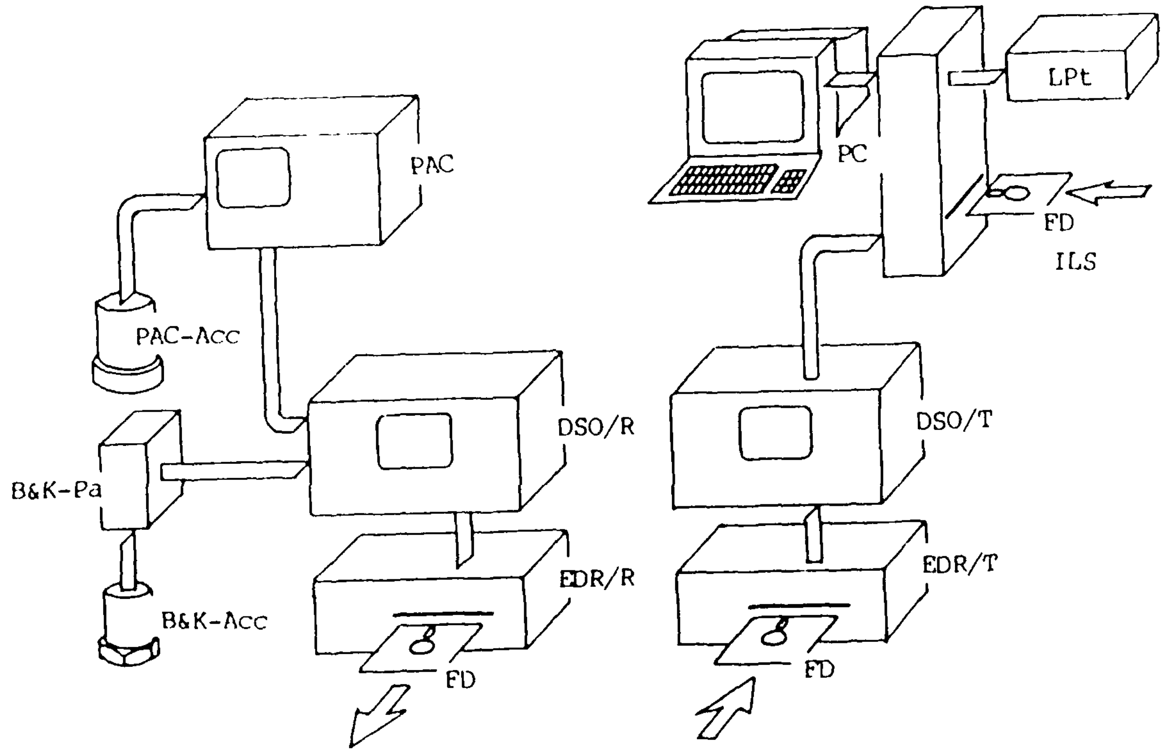


FIG 6.15 ATLAS 7016/3000

TYPICAL GRAPH OF CUMULATIVE EVENTS VS TIME



KEY

B&K-Acc, B&K-Pa	- Bruel & Kjaer 3484 accelerometer, 2635 preamplifier
PAC-Acc, PAC	- PAC accelerometer, AE recording station
DSO/R, /T	- Nicolet 4094 digital storage oscilloscope in recording (/R), transfer (/T) mode
EDR/R, /T	- Nicolet External Disk Recorder in /R, /T mode
PC	- PC HP Vectra
LPt	- Linear printer
ILS	- Interactive Laboratory System for processing data
FD	- Floppy disk with raw data

FIG 6.16 BLOCK DIAGRAM OF THE SYSTEM FOR DATA ACQUISITION AND WIDE BAND FREQUENCY ANALYSIS OF SEISMIC EVENTS

7.0 DATA

All Data collected during the two-year period of the Study is presented in this Section in a series of tables and graphs. The data includes elevations of the Mississippi River, acoustic emissions monitored and recorded at various locations on the cofferdam and pile movement point records. In general all data is identified by date occurred or obtained.

7.1 Mississippi River Elevation

Figures 7.1 through 7.7 provide a generally continuous record of the elevation of the Mississippi River at the project site during active Study periods. Figure 7.8 shows the variation of river elevation related to time of day during the flood event of October 1986.

7.2 Acoustic Emission (AE) Data

Figures 7.9 through 7.19 present the results of single and dual unit monitoring for various cofferdam cells or groups of cells from the inception of the Study through September 1986. In all cases both counts and events were recorded and the value of counts divided by events was utilized as the measure of AE activity. Figures 7.20 through 7.22 present the AE d[illegible]ecorded by semi-continuous monitoring at several individual cells on a single day during September 1986. Figure 7.23 provides average counts per minute divided by appropriate pencil break test values for six cells of interest (68, 71, 80, 87, 91 and 92) at which AE records were obtained on a regular basis during August and September, 1986.

Figure 7.24 shows AE counts per minute at each of the above six cells of interest during the high water period of October/ November, 1986. Figure 7.25 presents counts per minute recorded at cell 80 for various periods ranging from 15 minutes to one hour on successive days from October 2 through October 5, 1986.

AE counts per minute recorded at the six cells given above during semi-continuous monitoring from February 25 through April 23, 1987 are shown on Tables 7.1 and 7.2 as well as on Figures 7.26 and 7.27. The first Table or Figure provides undiscriminated data while the second shows discriminated data, i.e., data from which unusual high and low values have been eliminated. Figure 7.28 shows the same data in a semi-log plot. Figure 7.29 provides the initial AE data recorded from waveguides installed in the fill of cell 79.

As indicated earlier in this Report, continuous monitoring with the PAC ATLAS 7016/3000 equipment was commenced in August 1987. Figures 7.30 through 7.53 present the results of this monitoring from inception to March 25, 1988 on which date all monitoring was suspended. Average AE events per hour are shown for eight waveguide and seven sheet pile stations located between cells 76 and 80 as shown on Figure 6.4. Figures 7.47, 7.49 and 7.51 repeat the data shown on Figures 7.46, 7.48 and 7.50 using a semi-log scale for clarity. The frequency of the sensor used at each monitoring station and the ATLAS 7016/3000 channel on which the data was recorded are shown in Table 6.4. Table 7.3 indicates average events per hour at each monitoring station from November 3, 1987 to March 25, 1988. Table 7.4 provides data for three

monitoring stations at which data was recorded from both a low frequency (60 KHz) and a high frequency (150 KHz) sensor. Finally, Table 7.5 provides climatological data for the November/December 1987 period.

7.3 Pile Movement Point (PMP) Data

Pile Movement Points (PMP) were established at the time of cofferdam construction as a means of monitoring movement of the various cells and their elements due to forces imposed by differential head between the Mississippi River and the dewatered cofferdam. The location of these reference points and their relative movement is determined by the Corps of Engineers by optical survey methods on a regular basis. Figures 7.54 through 7.75 show this relative movement in graphic form from the beginning of the Study on March 1, 1986 until its completion on April 4, 1988. The ordinate of each Figure indicates whether movement into the cofferdam is presented as a positive or negative val .

7.4. Frequency Analysis Data

Figures 7.76 to 7.78 present a summary of waveforms recorded by individual sensors/accelerometers installed on sheetpiles or waveguides. Each waveform was subject to frequency analysis using the ILS software. T' o time windows for each waveform were analyzed to compare the frequency content of the initial part of the signal which best represents the direct wave from the source, and the major portion of the signal dominated by multiple reflections. The results of this analysis are given in Figures 7.79 to 7.90.

Figure 7.91 presents recorded waveforms normalized to comparable dynamic levels with a calibration factor (cal) given for each waveform for the voltage scale adjustment. Figures 7.92 to 7.99 show the evolution of the frequency spectra with increasing distance between the source and the sensor.

Figures 7.106 to 7.108 illustrate typical features of waveforms for all types of events as detected by both B&K and PAC sensors/accelerometers. References to the principal elements recognized as responsible for an event occurrence are given by each waveform. The real voltage amplitude of each waveform can be determined as voltage read from the Y coordinate multiplied by the calibration factor (cal). Frequency characteristics of each event are shown in figures 7.109 to 7.118.

CELL NUMBER

DATE	68.0	71.0	80.0	87.0	91.0	92.0
2/25	22.1	24.7	35.8	61.5	73.1	70.2
2/26	23.1	30.4	42.5	81.0	110.1	78.7
2/27	24.2	26.8	35.3	73.2	96.5	75.5
3/2	23.0	33.3	64.9	82.4	101.3	111.6
3/3	18.8	37.7	73.4	84.0	86.6	102.8
3/4	23.0	40.6	95.9	69.5	114.4	109.1
3/5	46.6	44.5	101.8	86.8	113.7	102.3
3/6	61.0	85.1	84.4	87.5	105.6	
3/9	73.6	98.2	95.3	101.9	98.8	103.1
3/10	84.4	103.2	96.0	99.7	91.4	96.0
3/11	72.0	71.2	101.6	79.6	85.9	83.6
3/12	102.0	70.4		87.9	117.9	100.9
3/13			89.1	90.6	101.3	
3/16	58.8	95.7	59.1	105.6	57.0	62.7
3/17	420.8	512.0	504.0	434.2	320.8	163.5
3/18	60.0	93.0	97.7	119.9	88.5	84.6
3/19	78.8	71.0	42.2	72.0	57.4	81.5
3/20	66.8	83.9	43.5	67.9	80.3	62.0
3/23	76.1	76.3	85.5	103.0	77.1	73.8
3/27	120.9	139.5	371.0	430.2	119.6	94.2
3/30	487.8	539.2	1075.2		836.7	716.2
3/31	451.5	614.3	1062.3	948.7	826.0	598.2
4/1	681.0	510.3	721.2	933.3	795.7	598.2
4/2	443.8	594.2	573.2	1064.5	915.8	946.0
4/3		307.0	733.8	729.5	323.8	
4/6	46.8	82.2	124.6	356.3	120.7	118.2
4/7	56.6	78.0	93.6	92.6	104.1	95.0
4/8	44.6	65.8	103.7	126.8	117.8	99.8
4/15			661.5	1292.6		
4/16	261.0	844.3	1730.3		308.0	501.3
4/17	431.5	470.2	1102.5	733.0	326.7	576.8
4/20	224.6	81.1	226.2	1218.0		
4/21			141.2	1305.0	960.9	34.9
4/22			100.7	32.0		257.0

TABLE 7.1
AVERAGE COUNTS PER MINUTE
(UNDISCRIMINATED)

FEBRUARY-APRIL 1986

CELL NUMBER

DATE	68.0	71.0	80.0	87.0	91.0	92.0
2/25	22.1	24.7	35.8	61.5	73.1	70.2
2/26	23.1	30.4	42.5	81.0	110.1	78.7
2/27	24.2	26.8	35.3	73.2	96.5	75.5
3/2	23.0	33.3	64.9	82.4	101.3	111.6
3/3	18.8	37.7	73.4	84.0	86.6	102.8
3/4	23.0	40.6	95.9	69.5	114.4	109.1
3/5	46.6	44.5	101.8	86.8	113.7	102.3
3/6	61.0	85.1	84.4	87.5	105.6	
3/9	73.6	98.2	95.3	101.9	98.8	103.1
3/10	84.4	103.2	96.0	99.7	91.4	96.0
3/11	72.0	71.2	101.6	79.6	85.9	83.6
3/12	102.0	70.4		87.9	117.9	100.9
3/13			89.1	90.6	101.3	
3/16	58.8	95.7	59.1	105.6	57.0	62.7
3/17	420.8	512.0	304.0	434.2	320.8	163.5
3/18	60.0	93.0	97.7	119.9	88.5	84.6
3/19	78.8	71.0	42.2	72.0	57.4	81.5
3/20	66.8	83.9	43.5	67.9	80.3	62.0
3/23	76.1	76.3	85.5	103.0	77.1	73.8
3/27	120.9	139.5	371.0	430.2	119.6	94.2
3/30	487.8	539.2	1075.2		836.7	716.2
3/31	451.5	614.3	1062.3	948.7	826.0	598.2
4/1	681.0	510.3	721.2	933.3	795.7	598.2
4/2	443.8	594.2	573.2	1064.5	915.8	946.0
4/3		307.0	733.8	729.5	323.8	
4/6	46.8	82.2	124.6	356.3	120.7	118.2
4/7	56.6	78.0	93.6	92.6	104.1	95.0
4/8	44.6	65.8	103.7	126.8	117.8	99.8
4/15			661.5	1292.6		
4/16	261.0	844.3	1730.3		308.0	501.3
4/17	431.5	470.2	1102.5	733.0	326.7	576.8
4/20	224.6	81.1	226.2			
4/21			141.2			34.9
4/22			100.7			

TABLE 7.2
AVERAGE COUNTS PER MINUTE
(DISCRIMINATED)

FEBRUARY-APRIL 1986

TABLE 7.3

AVERAGE EVENTS PER HOUR

MONITORING SUMMARY - NOVEMBER 3, 1987/MARCH 25, 1988

DATES	TIME *	WG-76. 30.S (HF) 01	WG-76. 70.C (HF) 02	WG-77 30.N (LF) 04	WG-77. 70.S (HF) 06	WG-77. 50.C (HF) 07	WG-77. 30.N (HF) 08	WG-79. 50.S (HF) 11	WG-79. 30.C (HF) 12	WG-77. 50.C (LF) 13
11/03-11/04	12.00	0.00	0.25	8.92	3.33	3.25	3.33	0.83	1.42	12.83
11/04-11/04	12.00	0.17	0.67	14.17	2.92	2.67	5.42	0.67	2.50	11.42
11/04-11/05	12.00	0.42	1.50	11.00	5.75	4.58	3.50	2.08	2.25	22.33
11/05-11/05	6.00	0.17	18.00	93.00	294.00	17.00	34.00	4.00	10.00	120.00
11/05-11/05	12.00	0.00	1.50	14.50	6.50	5.67	3.00	0.67	4.58	27.67
11/05-11/06	12.00	0.00	0.17	8.08	3.83	2.83	2.00	0.25	1.33	17.67
11/06-11/06	12.00	0.08	0.00	6.25	3.00	1.17	1.25	0.83	0.33	10.25
11/06-11/07	12.00	3.17	2.25	11.83	2.50	1.75	4.00	0.42	0.42	9.92
11/07-11/07	12.00	0.00	0.33	6.25	2.83	0.92	2.00	0.58	0.75	8.08
11/07-11/08	12.00	0.08	0.17	7.50	3.92	1.00	2.33	0.58	0.92	6.67
11/08-11/08	12.00	0.08	0.50	6.08	3.42	1.00	1.75	0.33	0.33	7.42
11/08-11/09	11.10	0.00	0.36	9.13	17.73	2.06	3.31	0.36	0.54	7.88
11/9-11/10	12.00	0.00	0.00	0.08	0.00	0.00	0.00	0.08	0.00	0.08
11/10-11/10	12.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11/10-11/11	12.00	0.00	0.00	0.17	0.00	0.00	0.17	0.00	0.00	0.00
11/11-11/11	12.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.08
11/11-11/12	12.00	0.00	0.00	0.25	0.08	0.08	0.17	0.00	0.00	0.17
11/12-11/12	12.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11/12-11/13	12.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00
11/13-11/14	12.00	0.17	0.25	7.25	2.58	1.08	1.92	0.67	1.08	7.58
11/14-11/14	12.00	0.25	0.42	5.75	1.92	1.67	1.33	0.50	0.83	5.92
11/14-11/15	12.00	0.25	1.17	9.00	4.17	3.17	2.17	0.75	1.25	15.83
11/15-11/15	12.00	0.08	0.75	4.92	2.67	1.83	1.08	0.25	0.58	11.17
11/15-11/16	12.00	0.17	1.08	4.75	1.67	2.67	1.50	0.67	0.67	7.08
11/16-11/16	12.00	0.08	1.50	3.67	2.50	2.00	1.00	0.17	0.75	7.92
11/16-11/16	9.67	0.10	1.24	8.38	2.17	1.55	2.28	0.41	0.93	5.89
11/16-11/17	12.00	0.17	0.92	7.33	2.25	2.67	1.67	0.33	1.50	8.50
11/17-11/17	12.00	0.00	0.50	5.83	3.33	1.25	1.00	0.42	0.67	7.25
11/17-11/18	12.00	0.08	1.17	13.67	5.17	1.75	3.50	0.75	1.67	9.42
11/18-11/18	12.00	0.17	0.67	9.00	3.75	1.75	2.25	0.17	3.75	7.25
11/18-11/19	12.00	0.00	0.25	8.83	2.50	1.25	3.50	0.67	0.50	5.42
11/19-11/19	12.00	0.08	0.75	7.08	2.83	3.17	1.67	0.67	1.75	10.25
11/19-11/20	12.00	0.00	0.25	6.33	2.42	1.33	2.08	0.42	1.08	8.08
11/20-11/20	10.85	0.28	0.65	11.71	2.40	2.67	4.42	0.28	2.40	10.05
11/23-11/23	12.00	0.08	0.58	9.42	3.33	1.17	1.42	0.17	1.50	5.00
11/23-11/24	12.00	0.00	0.83	7.08	1.50	1.00	1.33	0.33	1.58	4.33
11/24-11/24	12.00	0.25	4.75	9.00	3.00	0.67	2.67	0.17	1.00	5.25
11/24-11/25	12.00	0.00	0.42	18.42	3.08	0.42	0.92	0.67	7.00	5.00
11/25-11/26	12.00	0.00	0.67	3.92	1.83	1.17	1.08	0.25	0.42	4.67
11/26-11/27	11.13	0.18	0.27	9.70	3.86	0.90	0.54	0.90	0.54	3.32
11/27-11/28	12.00	0.08	1.92	5.58	2.25	1.17	0.67	0.67	0.50	4.25
11/29-11/29	12.00	0.17	0.42	5.17	1.58	0.50	1.25	0.25	0.75	2.75
11/30-12/01	12.00	0.08	0.83	4.33	2.33	0.50	0.67	0.50	0.75	7.00
12/01-12/01	11.08	0.09	0.63	15.88	3.07	0.72	0.63	0.72	6.23	4.87
12/04-12/05	12.00	0.00	0.42	2.92	3.83	0.75	0.92	0.92	0.67	3.00
12/05-12/05	12.00	0.00	0.50	4.83	1.67	1.17	1.33	3.50	0.50	6.42
12/05-12/06	12.00	0.00	0.50	2.25	1.92	1.08	0.75	0.75	0.50	3.92
12/06-12/06	12.00	0.08	0.58	2.67	3.00	1.33	0.75	0.33	0.58	5.17
12/06-12/07	12.00	0.08	0.67	2.67	2.33	0.50	0.83	0.08	0.50	5.75
12/07-12/07	10.83	0.00	0.37	2.68	1.94	0.46	0.65	2.40	0.74	3.32
12/07-12/08	10.00	0.00	4.60	4.50	7.00	1.10	0.50	1.30	0.90	4.20
12/08-12/08	10.00	0.10	1.90	3.30	2.00	0.60	0.90	0.30	0.70	6.40
12/08-12/08	10.00	0.20	1.40	5.40	2.60	0.90	1.60	0.40	1.10	3.10
12/08-12/09	10.00	0.10	0.50	3.20	1.70	1.50	1.20	1.00	1.70	5.10
12/09-12/09	10.00	0.00	0.70	4.80	3.30	0.20	1.40	0.20	1.20	2.50
12/09-12/10	10.00	0.10	0.40	4.00	3.60	0.90	1.10	0.20	1.10	6.90
12/10-12/10	10.00	0.10	0.90	2.50	2.80	1.10	1.00	0.40	0.90	5.20
12/10-12/10	10.00	0.00	1.00	2.60	41.30	0.50	0.50	0.90	4.30	7.20
12/11-12/11	4.93	0.00	0.41	3.85	4.67	0.41	0.81	1.42	14.40	2.23

TABLE 7.3 (Continued)

AVERAGE EVENTS PER HOUR

MONITORING SUMMARY - NOVEMBER 3, 1987/MARCH 25, 1988

DATES	TIME *	WG-76, 30.S (LF) 01	WG-76, 70.C (LF) 02	WG-77, 70.S (LF) 06	WG-77, 50.C (LF) 07	WG-77, 30.N (LF) 08	WG-79, 50.S (LF) 11	WG-79, 30.C (LF) 12	OPEN 13
01/22-01/22	10.00	15.30	7.10	1.50	55.10	1.90	0.30	3.00	0.00
01/23-01/23	10.00	1.20	2.50	1.00	20.00	5.90	0.10	1.80	0.00
01/23-01/23	10.00	0.60	1.10	14.40	51.60	2.60	0.80	4.60	0.00
01/23-01/24	10.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00
01/24-01/24	10.00	0.40	1.80	2.50	2.80	2.90	1.10	2.50	0.00
01/24-01/24	10.00	0.50	1.80	1.10	2.10	1.30	0.10	2.20	0.00
01/24-01/25	10.00	1.40	0.80	1.10	0.50	1.90	0.40	1.70	0.00
01/25-01/25	2.40	0.42	2.08	2.08	1.67	0.83	0.00	2.08	0.00
01/25-01/25	10.00	1.10	1.50	2.40	1.30	2.10	1.10	1.80	0.00
01/25-01/26	10.00	0.80	3.30	3.40	2.00	3.30	0.10	3.80	0.00
01/26-01/26	10.00	0.30	2.60	0.90	8.60	3.00	0.90	3.80	0.00
01/26-01/27	10.00	0.50	2.70	0.70	0.30	2.20	0.00	1.20	0.00
01/27-01/27	10.00	14.90	10.60	1.80	44.30	5.70	0.20	10.50	0.00
01/27-01/28	10.00	1.20	2.00	3.50	5.20	1.80	1.00	1.50	0.00
01/28-01/28	10.00	2.00	4.70	26.60	13.80	2.10	0.20	4.80	0.00
01/28-01/28	10.00	2.80	6.40	4.70	8.80	2.80	0.40	3.50	0.00
01/28-01/29	10.00	0.30	4.60	15.10	5.40	1.30	0.60	1.30	0.00
01/29-01/29	5.90	0.85	2.71	16.27	22.54	1.86	0.34	2.71	0.00
01/29-01/29	10.00	1.30	2.30	0.70	7.20	7.10	0.70	4.50	0.00
01/29-01/30	10.00	0.00	1.20	0.70	2.80	4.60	0.10	1.30	0.00
01/30-01/30	10.00	1.80	5.90	0.90	4.50	8.50	1.90	4.20	0.00
01/30-01/31	10.00	0.20	2.40	0.10	0.70	1.50	0.00	0.90	0.00
01/31-01/31	10.00	1.40	1.00	0.30	1.40	3.00	0.30	4.30	0.00
01/31-01/31	10.00	0.30	3.00	0.10	2.10	1.90	0.20	3.50	0.00
01/31-02/01	10.00	0.50	2.20	0.50	4.90	2.50	0.40	4.00	0.00
02/01-02/01	10.00	0.40	0.30	0.00	14.40	0.10	0.00	1.10	0.00
02/01-02/02	12.00	0.67	0.92	1.08	71.92	2.67	0.33	3.08	0.00
02/02-02/02	12.00	0.33	0.33	0.17	0.50	1.50	0.67	0.50	0.00
02/02-02/03	12.00	0.08	0.42	0.58	1.17	1.50	0.08	0.58	0.00
02/03-02/03	12.00	0.25	0.25	0.50	1.67	1.92	0.17	2.50	0.00
02/03-02/04	12.00	0.75	1.08	0.58	1.75	1.67	0.83	1.92	0.00
02/04-02/04	12.00	0.92	1.75	1.58	1.42	3.00	2.42	1.75	0.00
02/04-02/05	12.00	1.08	2.42	1.92	2.83	3.25	0.92	2.08	0.00
02/05-02/05	10.87	0.64	4.32	7.08	3.40	3.04	0.37	2.76	0.00
02/06-02/06	12.00	0.67	2.33	0.83	4.75	1.92	0.17	1.08	0.00
02/06-02/07	12.00	1.17	1.50	0.33	2.33	3.25	1.50	1.42	0.00
02/07-02/07	12.00	0.42	1.50	2.08	6.50	2.25	0.33	1.75	0.00
02/07-02/08	12.00	0.67	2.00	0.42	44.58	2.08	0.00	1.42	0.00
02/08-02/08	12.00	1.75	3.00	57.67	10.08	1.42	0.17	1.67	0.00
02/08-02/09	12.00	3.08	1.67	0.42	0.75	1.58	0.25	1.00	0.00
02/09-02/09	12.00	2.17	1.58	8.75	8.50	2.50	0.33	3.00	0.00
02/09-02/10	12.00	0.25	3.67	2.17	3.67	1.83	0.25	3.08	0.00
02/10-02/10	12.00	0.42	2.33	0.58	0.25	1.17	0.08	0.67	0.00
02/10-02/11	12.00	0.17	3.00	0.75	1.58	2.33	0.00	0.58	0.00
02/11-02/11	12.00	1.08	2.42	2.08	6.08	3.42	0.08	2.92	0.00
02/11-02/12	11.04	2.63	13.04	6.97	15.17	15.94	3.89	12.41	0.00
02/12-02/12	12.00	6.67	59.17	13.75	29.25	93.50	3.50	21.08	0.00
02/12-02/13	12.00	1.00	26.83	0.67	11.42	13.17	0.17	6.33	0.00
02/13-02/13	12.00	0.75	13.58	0.08	5.42	19.33	0.75	6.00	0.00
02/13-02/14	12.00	4.00	5.58	3.25	2.42	23.25	0.92	3.17	0.00
02/14-02/14	12.00	0.25	2.67	1.00	1.00	23.75	0.58	2.58	0.00
02/14-02/15	12.00	0.25	5.08	7.75	5.33	11.25	0.42	1.33	0.00
02/15-02/16	12.00	0.67	2.92	0.50	1.83	2.25	0.33	1.42	0.00
02/16-02/16	12.00	0.50	5.92	3.33	17.50	2.92	0.25	2.92	0.00
02/16-02/17	12.00	0.75	8.50	2.42	7.33	3.75	0.33	3.42	0.00
02/17-02/17	12.00	1.00	3.42	4.08	35.25	3.92	0.50	6.75	0.00
02/17-02/18	12.00	0.50	3.17	2.42	2.75	3.50	0.17	2.50	0.00

TABLE 7.3 (Continued)

AVERAGE EVENTS PER HOUR

MONITORING SUMMARY - NOVEMBER 3, 1987/MARCH 25, 1988

DATES	TIME *	WG-76. 30.S (LF) 01	WG-76. 70.C (LF) 02	WG-77. 70.S (LF) 06	WG-77. 50.C (LF) 07	WG-77. 30.N (LF) 08	WG-79. 50.S (LF) 11	WG-79. 30.C (LF) 12	OPEN 13
02/18-02/18	12.00	0.83	3.00	1.75	25.33	3.33	0.33	6.83	0.00
02/18-02/19	12.00	0.08	4.00	1.00	13.75	3.50	0.83	1.25	0.00
02/19-02/19	12.00	0.33	2.83	6.42	30.67	2.08	0.67	4.92	0.00
02/19-02/20	12.00	0.25	8.67	4.50	17.00	4.58	0.08	3.17	0.00
02/20-02/20	12.00	0.25	2.42	3.83	7.83	2.42	0.25	2.75	0.00
02/20-02/21	12.00	0.50	2.58	0.58	0.83	2.50	1.33	0.67	0.00
02/21-02/21	19.93	1.51	13.55	10.04	39.44	10.59	2.21	9.83	0.00
02/24-02/25	12.00	614.33	735.00	142.08	149.08	294.42	801.75	212.00	0.00
02/25-02/25	12.00	0.33	1.00	1.17	1.08	1.75	0.17	2.25	0.00
02/25-02/26	12.00	0.58	268.17	26.33	18.33	2.00	0.17	8.67	0.00
02/26-02/26	12.00	0.42	1.83	2.17	2.25	1.50	0.17	2.00	0.00
02/26-02/27	12.00	0.92	168.83	36.92	24.92	1.83	0.42	7.33	0.00
02/27-02/27	12.00	0.33	15.83	1.17	1.67	2.08	0.42	6.58	0.00
02/27-02/28	12.00	0.58	2.67	0.67	0.67	1.92	0.25	1.08	0.00
02/28-02/28	12.00	0.58	6.33	0.75	2.00	3.17	1.08	4.08	0.00
02/28-02/29	12.00	62.00	85.33	0.08	1.33	2.17	0.25	2.25	0.00
02/29-02/29	12.00	5.17	24.92	50.67	61.58	174.17	239.42	165.58	0.00
02/29-03/01	12.00	245.58	448.67	5.17	72.25	33.08	370.75	11.67	0.00
03/01-03/02	12.00	962.50	205.33	8.00	129.17	12.25	350.33	4.75	0.00
03/02-03/02	12.00	1588.58	726.67	8.33	42.92	39.25	485.75	9.42	0.00
03/02-03/03	12.00	316.08	236.17	10.42	20.08	66.58	426.42	19.08	0.00
03/03-03/03	12.00	706.42	7.92	2.17	14.33	132.33	120.33	17.33	0.00
03/03-03/04	12.00	310.00	10.00	1.08	3.42	8.33	336.92	0.83	0.00
03/04-03/04	9.65	211.30	18.55	0.10	14.72	1.97	10.88	0.83	0.00
03/04-03/05	12.00	2809.58	430.92	8.25	640.83	1090.33	981.08	85.25	0.00
03/05-03/05	12.00	81.92	35.58	0.25	21.58	357.33	13.42	3.58	0.00
03/05-03/06	12.00	29.00	11.08	0.58	2.25	440.83	3.08	1.25	0.00
03/06-03/06	12.00	160.67	52.83	0.58	9.50	43.75	92.42	8.42	0.00
03/06-03/07	12.00	244.00	11.42	0.33	8.00	16.17	45.67	7.58	0.00

DATES	TIME *	WG-76. 30.S (LF) 01	WG-76. 70.C (LF) 02	WG-77. 70.S (LF) 06	WG-77. 50.C (HF) 07	WG-77. 30.' [illegible] 08	WG-79. 50.S (LF) 11	WG-79. 30.C (LF) 12	WG-77. 50.C (LF) 13
03/07-03/07	12.00	276.17	10.25	0.00	9.92	102.92	76.17	2.42	0.00
03/07-03/07	10.76	2250.37	345.45	7.25	657.53	144.24	836.90	69.14	0.00
03/21-03/22	12.00	0.00	0.00	41.92	1180.17	24.58	60.33	204.58	17.83
03/22-03/22	12.00	0.00	0.00	1.08	692.42	13.42	13.00	69.75	22.25
03/22-03/23	12.00	0.00	0.00	1.92	881.50	9.08	5.50	23.67	24.08
03/23-03/23	12.00	0.00	0.00	120.83	290.67	398.67	549.25	140.83	125.58
03/23-03/24	12.00	0.00	0.00	1.83	114.58	22.58	2.00	6.92	3.00
03/24-03/24	12.00	0.00	0.00	1.50	286.83	237.42	3.42	48.50	27.67
03/24-03/25	12.00	0.00	0.00	1.92	81.00	79.75	6.25	46.25	1.42
03/25-03/25	9.90	0.00	0.00	0.81	95.05	17.68	1.72	47.98	0.61

TABLE 7.3 (Continued)

AVERAGE EVENTS PER HOUR

MONITORING SUMMARY - NOVEMBER 3, 1987/MARCH 25, 1988

DATES	TIME *	SP-76/77 (HF) 05	SP-77 (HF) 09	SP-78/79 (HF) 10	SP-79 (HF) 14	SP-79/80 (HF) 15	SP-80 (HF) 16	SP-77 (LF) 03
11/03-11/04	12.00	51.92	39.17	19.67	53.50	48.17	32.25	124.50
11/04-11/04	12.00	134.67	80.83	124.08	145.92	96.33	79.83	263.25
11/04-11/05	12.00	254.50	247.92	343.08	200.58	149.58	130.67	1531.25
11/05-11/05	6.00	1103.00	2950.00	1550.00	1896.00	1258.00	3381.00	24478.00
11/05-11/05	12.00	910.83	116.83	140.58	374.83	127.25	186.58	771.33
11/05-11/06	12.00	35.75	32.00	25.17	32.75	39.00	58.00	61.83
11/06-11/06	12.00	33.75	28.42	20.08	34.17	38.67	55.42	119.00
11/06-11/07	12.00	433.67	249.42	348.00	374.17	278.08	345.25	1563.42
11/07-11/07	12.00	42.17	40.33	25.75	66.42	71.17	58.50	124.08
11/07-11/08	12.00	93.08	90.75	101.83	104.83	46.67	117.33	566.50
11/08-11/08	12.00	24.25	46.75	18.42	32.33	11.08	47.33	191.00
11/08-11/09	11.10	234.74	243.33	105.91	1555.24	36.08	118.89	1058.55
11/9-11/10	12.00	0.00	0.25	0.42	1.58	0.67	0.58	1.08
11/10-11/10	12.00	1.42	0.42	0.25	0.50	0.17	1.00	7.00
11/10-11/11	12.00	0.00	0.08	0.00	0.08	0.00	0.08	0.25
11/11-11/11	12.00	0.33	0.08	0.17	0.75	0.00	0.17	0.17
11/11-11/12	12.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00
11/12-11/12	12.00	2.08	0.08	0.25	0.50	0.08	0.83	0.33
11/12-11/13	12.00	0.00	0.08	0.00	0.00	0.08	0.17	0.00
11/13-11/14	12.00	29.00	40.08	25.17	87.33	55.50	78.00	130.08
11/14-11/14	12.00	12.33	28.83	19.17	52.83	30.67	28.00	71.58
11/14-11/15	12.00	19.75	47.67	27.33	94.33	83.08	47.00	170.25
11/15-11/15	12.00	10.42	25.17	12.50	48.92	56.33	27.00	107.75
11/15-11/16	12.00	77.17	53.08	57.83	58.58	40.92	57.25	219.33
11/16-11/16	12.00	97.67	5499.17	100.50	121.75	121.33	129.75	609.08
11/16-11/16	9.67	1043.43	22667.11	1727.30	666.60	726.27	566.60	2629.68
11/16-11/17	12.00	410.00	224.00	426.58	2.25	2.67	1.67	2381.00
11/17-11/17	12.00	116.08	44.00	56.25	59.83	39.33	62.08	154.33
11/17-11/18	12.00	193.83	81.67	109.08	93.75	51.58	95.25	489.00
11/18-11/18	12.00	58.08	27.17	27.08	40.33	40.08	25.92	304.00
11/18-11/19	12.00	13.75	10.00	14.58	29.67	34.58	12.92	17.50
11/19-11/19	12.00	82.83	33.42	41.67	58.50	61.83	62.58	57.50
11/19-11/20	12.00	148.25	61.42	84.25	103.67	90.50	101.17	444.50
11/20-11/20	10.85	863.69	185.62	67.56	185.81	424.42	455.48	2149.49
11/23-11/23	12.00	34.75	39.17	28.00	49.33	69.33	53.67	79.00
11/23-11/24	12.00	258.67	193.92	212.25	343.08	229.25	401.92	1762.75
11/24-11/24	12.00	1711.92	722.00	1414.92	1835.33	1135.17	1585.50	12211.67
11/24-11/25	12.00	100.42	52.00	76.17	101.33	51.00	61.75	758.75
11/25-11/26	12.00	22.50	37.92	16.50	681.75	165.42	44.33	129.83
11/26-11/27	11.13	16.08	7.55	11.59	15.36	9.34	19.77	101.62
11/27-11/28	12.00	188.42	82.83	133.67	191.08	141.00	121.75	1189.42
11/29-11/29	12.00	1707.75	704.58	1212.25	1064.33	1157.83	1042.25	1583.92
11/30-12/01	12.00	53.33	18.33	29.00	27.50	19.08	26.33	75.25
12/01-12/01	11.08	86.37	44.22	53.52	50.36	47.29	45.31	93.86
12/04-12/05	12.00	14.25	22.75	16.75	23.67	36.58	31.42	54.33
12/05-12/05	12.00	29.92	44.50	19.08	45.17	28.42	62.83	115.58
12/05-12/06	12.00	19.50	23.08	15.42	24.58	33.25	54.50	79.50
12/06-12/06	12.00	127.17	40.33	184.67	93.42	35.00	58.67	264.33
12/06-12/07	12.00	73.50	35.58	122.33	81.92	29.67	58.67	378.42
12/07-12/07	10.83	300.28	147.09	480.15	326.50	193.35	130.29	1539.89
12/07-12/08	10.00	99.60	50.60	106.60	104.10	56.00	83.70	515.60
12/08-12/08	10.00	5.30	1.40	5.90	4.30	1.30	13.40	6.60
12/08-12/08	10.00	78.30	20.60	31.20	46.70	23.50	51.60	47.20
12/08-12/09	10.00	340.30	100.80	160.90	231.10	194.00	210.60	465.50
12/09-12/09	10 00	40.40	31.00	33.40	42.10	36.00	30.00	59.00
12/09-12/10	10.00	12.90	11.20	23.60	17.10	33.30	15.00	29.70
12/10-12/10	10.00	8.80	851.70	9.30	8.00	4.80	8.20	10.90
12/10-12/10	10.00	31.00	843.00	36.10	71.30	73.50	32.90	42.60
12/11-12/11	4.93	55.98	4006.90	53.35	50.51	43.00	38.95	82.96

TABLE 7.3 (Continued)

AVERAGE EVENTS PER HOUR

MONITORING SUMMARY - NOVEMBER 3, 1987/MARCH 25, 1988

DATES	TIME *	SP-76 (LF) 04	SP-76/77 (HF) 05	SP-77 (LF) 09	SP-78/79 (HF) 10	SP-79 (LF) 14	SP-79/80 (LF) 15	SP-80 (HF) 15
01/22-01/22	10.00	384.30	11.70	243.30	57.30	200.70	25.10	12.10
01/23-01/23	10.00	107.70	3.70	52.70	21.80	34.00	7.80	11.60
01/23-01/23	10.00	113.80	3.60	175.50	36.50	418.90	13.20	16.00
01/23-01/24	10.00	0.70	0.00	0.60	3.20	1.90	0.00	0.00
01/24-01/24	10.00	1613.60	85.20	1763.40	367.40	1129.40	334.10	376.80
01/24-01/24	10.00	85.30	0.30	88.00	13.90	35.50	13.50	4.90
01/24-01/25	10.00	19535.50	474.00	12563.80	2121.00	19244.30	1313.60	990.50
01/25-01/25	2.40	4578.33	395.00	2712.50	1688.33	4067.92	1260.00	270.83
01/25-01/25	10.00	3931.30	239.00	2202.70	1044.20	3785.50	1704.40	258.30
01/25-01/26	10.00	3193.50	92.90	804.30	339.00	1617.30	546.90	189.10
01/26-01/26	10.00	429.50	1.50	102.10	26.40	182.70	27.30	6.20
01/26-01/27	10.00	114.30	0.70	47.20	14.20	7.90	4.70	3.70
01/27-01/27	10.00	243.80	30.40	275.10	74.90	120.70	17.00	115.40
01/27-01/28	10.00	179.70	5.20	217.50	41.20	134.60	13.70	17.10
01/28-01/28	10.00	122.50	30.00	195.10	112.10	67.10	15.60	24.10
01/28-01/28	10.00	183.10	1.60	168.20	20.90	95.90	21.90	15.20
01/28-01/29	10.00	90.80	0.70	57.10	9.00	21.60	3.60	[illegible] 10
01/29-01/29	5.90	316.95	15.42	434.07	98.81	172.03	166.95	5[illegible].31
01/29-01/29	10.00	291.90	4.20	695.80	86.80	363.10	149.70	42.20
01/29-01/30	10.00	699.90	46.10	1750.80	284.60	591.90	272.90	165.50
01/30-01/30	10.00	3537.00	438.10	8753.30	2023.60	1455.60	931.50	590.00
01/30-01/31	10.00	53.40	3.00	2850.40	117.80	136.00	109.60	25.60
01/31-01/31	10.00	16592.90	178.80	11323.30	1809.40	13756.10	1280.20	825.20
01/31-01/31	10.00	5795.20	31.20	3614.60	337.10	3695.40	187.10	129.00
01/31-02/01	10.00	96969.60	63.20	6143.30	532.00	6836.80	358.10	258.20
02/01-02/01	10.00	453.30	2.00	221.10	15.40	369.50	11.80	10.30
02/01-02/02	12.00	2790.25	9.75	738.00	112.42	4429.92	43.67	307.83
02/02-02/02	12.00	165.75	3.50	105.58	12.92	122.42	5.58	5.08
02/02-02/03	12.00	43391.67	9065.33	46022.00	17639.33	51864.42	21471.08	17552.58
02/03-02/03	12.00	1897.00	249.50	2509.67	978.67	3471.42	512.92	2877.33
02/03-02/04	12.00	1492.75	131.92	2234.75	520.83	4322.83	161.83	344.58
02/04-02/04	12.00	2994.08	149.83	4659.58	650.00	8967.83	387.92	713.25
02/04-02/05	12.00	3879.75	29.50	4556.17	433.00	3907.58	486.92	139.17
02/05-02/05	10.87	606.99	19.14	769.27	94.11	348.67	226.77	50.32
02/06-02/06	12.00	61.58	0.58	105.50	12.92	36.83	37.92	8.67
02/06-02/07	12.00	766.08	44.92	571.42	168.58	431.50	158.92	97.50
02/07-02/07	12.00	679.92	51.17	596.67	172.25	540.25	255.42	110.92
02/07-02/08	12.00	171.67	130.17	450.92	226.67	160.83	44.25	59.25
02/08-02/08	12.00	3589.58	5.67	1036.33	74.00	507.33	25.42	23.75
02/08-02/09	12.00	1841.42	4.33	775.58	41087.17	1484.75	121.00	189.42
02/09-02/09	12.00	295.92	66.67	546.00	257.42	415.42	74.3[illegible]	96.58
02/09-02/10	12.00	742.42	53.67	592.67	297.08	2.17	3.67	1.83
02/10-02/10	12.00	45556.83	4969.42	43996.08	17781.83	50025.58	12303.58	11326.42
02/10-02/11	12.00	24198.33	3831 67	27280.33	14803.42	37015.58	14542.00	1945.92
02/11-02/11	12.00	15988.92	2352.83	8096.83	6054.33	16822.92	6228.83	557.42
02/11-02/12	11.04	223.91	39.58	362.14	137.50	325.00	42.12	65.94
02/12-02/12	12.00	5133.42	198.00	4134.00	1468.92	6203.50	1939.42	372.42
02/12-02/13	12.00	289.33	11.92	274.50	88.92	513.50	29.58	9.67
02/13-02/13	12.00	56.50	9.50	164.67	30.42	64.75	5.00	12.25
02/13-02/14	12.00	217.08	22.08	456.33	284.75	328.42	31.50	25.75
02/14-02/14	12.00	143.67	7.83	442.17	102.33	119.58	26.17	26.92
02/14-02/15	12.00	2401.67	74.42	1634.17	575.75	3079.58	1182.08	215.67
02/15-02/16	12.00	162.50	31.17	188.25	56.33	140.08	42.83	44.75
02/16-02/16	12.00	388.50	40.00	307.92	83.08	603.50	56.00	66.75
02/16-02/17	12.00	259.75	1.67	206.50	29.17	663.50	23.92	76.17
02/17-02/17	12.00	1053.42	3.08	192.92	183.58	955.92	19.58	231.33
02/17-02/18	12.00	89.58	1.08	119.08	13.33	184.50	14.08	5.33

TABLE 7.3 (Continued)

AVERAGE EVENTS PER HOUR

MONITORING SUMMARY - NOVEMBER 3, 1987/MARCH 25, 1988

DATES	TIME *	SP-76 (LF) 04	SP-76/77 (HF) 05	SP-77 (LF) 09	SP-78/79 (HF) 10	SP-79 (LF) 14	SP-79/80 (LF) 15	SP-80 (HF) 16
02/18-02/18	12.00	274.08	4.17	181.42	63.17	285.33	25.33	17.25
02/18-02/19	12.00	1913.50	17.50	1133.17	254.83	1264.25	89.67	69.75
02/19-02/19	12.00	12235.67	189.08	9903.08	1377.92	10280.75	935.67	854.83
02/19-02/20	12.00	160.92	7.17	95.75	75.42	476.67	25.75	21.25
02/20-02/20	12.00	840.67	11.67	422.67	152.58	1959.33	142.83	17.17
02/20-02/21	12.00	1483.17	32.67	1196.17	288.92	2624.00	220.92	169.17
02/21-02/21	19.93	10323.13	211.34	8168.84	1465.08	10690.17	911.24	790.62
02/24-02/25	12.00	9351.50	252.17	4559.25	1357.92	6654.50	1256.00	629.33
02/25-02/25	12.00	363.00	8.67	286.17	72.42	452.83	157.33	58.08
02/25-02/26	12.00	739.58	66.42	774.67	194.42	955.83	133.92	139.50
02/26-02/26	12.00	112.42	1.75	131.92	11.17	86.25	13.83	13.58
02/26-02/27	12.00	364.17	11.17	409.08	51.92	574.17	81.25	54.83
02/27-02/27	12.00	724.58	90.67	630.50	210.92	759.42	567.83	227.83
02/27-02/28	12.00	1527.67	10.75	308.58	168.75	1011.17	38.83	15.50
02/28-02/28	12.00	1341.92	4.33	247.92	25.33	560.83	27.08	18.67
02/28-02/29	12.00	133.58	8.17	213.75	30.00	244.33	21.00	19.92
02/29-02/29	12.00	3897.00	38.75	1411.75	527.83	1696.75	190.25	64.67
02/29-03/01	12.00	193.67	5.25	126.67	33.33	542.17	20.00	20.08
03/01-03/02	12.00	853.17	34.00	767.83	149.83	1176.00	106.33	79.25
03/02-03/02	12.00	4803.17	41.08	2779.83	473.50	3951.75	325.67	149.83
03/02-03/03	12.00	7341.92	36.67	4187.67	762.00	4781.08	320.75	171.83
03/03-03/03	12.00	37185.25	1699.00	24732.00	5851.58	25568.83	7478.42	4427.75
03/03-03/04	12.00	28760.17	12787.67	24450.58	18824.58	28056.17	21815.83	15975.17
03/04-03/04	9.65	43136.48	6129.64	36892.12	15495.34	53518.24	20836.48	9816.17
03/04-03/05	12.00	4818.75	205.08	2082.75	1390.50	9650.58	936.33	399.58
03/05-03/05	12.00	2809.50	82.75	895.42	796.42	5239.67	678.33	83.75
03/05-03/06	12.00	689.33	93.17	464.83	298.08	848.75	142.25	166.83
03/06-03/06	12.00	470.00	2.50	124.75	56.42	920.50	14.67	14.50
03/06-03/07	12.00	467.75	13.08	386.67	158.50	912.17	75.58	79.00

DATES	TIME *	SP-76 (LF) 04	SP-76/77 (HF) 05	SP-77 (LF) 09	SP-78/79 (HF) 10	SP-79 (LF) 14	SP-79/80 (LF) 15	SP-80 (HF) 16
03/07-03/07	12.00	268.50	6.58	167.58	43.25	1336.83	19.33	40.25
03/07-03/07	10.76	130.02	8.18	51.02	42.47	440.43	8.83	17.38
03/21-03/22	12.00	0.00	8.33	789.17	55.92	1481.75	542.17	105.33
03/22-03/22	12.00	0.00	17.58	290.00	88.75	492.50	432.83	227.67
03/22-03/23	12.00	0.00	31.08	971.25	426.08	474.08	1305.67	434.42
03/23-03/23	12.00	0.00	61.83	417.08	212.92	254.67	822.67	282.58
03/23-03/24	12.00	0.00	26.83	494.83	95.25	239.67	745.58	215.83
03/24-03/24	12.00	0.00	309.92	1233.67	1437.25	631.92	3093.42	1177.67
03/24-03/25	12.00	0.00	2109.50	10349.42	7063.17	7697.92	17018.08	4844.67
03/25-03/25	9.90	0.00	25.35	218.69	106.16	235.56	1464.55	98.28

TABLE 7.4

COMPARISON OF LOW AND HIGH FREQUENCY EVENTS

SEPTEMBER 1987-DECEMBER 1988

PERIOD	HRS	WG-77.50.C			WG-77.30.N			SP-77		
		CH.13.LF	CH.7.HF	LF/HF	CH.4.LF	CH.8.HF	LF/HF	CH.3.LF	CH.9.HF	LF/HF
Sep 24/26	22.0	263	58	4.5	—	—	—	—	—	—
Sep 26/01	24.0	248	50	5.0	—	—	—	—	—	—
	24.0	237	39	6.1	—	—	—	—	—	—
	24.0	217	37	5.9	—	—	—	—	—	—
	24.0	1050	302	3.5	—	—	—	—	—	—
	23.5	401	109	3.7	—	—	—	—	—	—
Oct 01/05	16.7	496	89	5.6	—	—	—	—	—	—
Oct 10/12	16.7	262	64	4.1	—	—	—	—	—	—
Oct 12/13	16.7	192	27	7.1	—	—	—	—	—	—
Oct 14/16	16.7	157	19	8.3	—	—	—	—	—	—
Oct 31/02	16.7	564	129	4.4	—	—	—	—	—	—
Nov 02/03	16.7	223	61	3.7	—	—	—	—	—	—
Nov 03/05	24.0	291	71	4.1	277	105	2.6	4653	1440	3.2
	17.9	388	76	5.1	225	76	3.0	42853	2950	14.5
Nov 05/09	24.0	544	102	5.3	271	60	4.5	10007	1786	5.6
	24.0	242	35	6.9	217	63	3.4	20189	3334	6.1
	24.0	147	23	6.4	165	52	3.2	8287	1573	5.3
	12.5	177	35	5.1	175	58	3.0	14116	3285	4.3
Nov 13/16	24.0	162	33	4.9	156	39	4.0	2420	827	2.9
	24.0	325	60	5.4	167	39	4.3	3336	874	3.8
	24.0	180	56	3.2	101	30	3.4	9941	66627	-6.7
	11.3	57	15	3.8	81	22	3.7	25429	219191	-8.6
Nov 16/20	24.0	189	47	4.0	158	32	4.9	30424	3216	9.5
	24.0	178	36	4.9	214	69	3.1	3858	446	8.7
	24.0	220	54	4.1	161	45	3.6	6024	1138	5.3
	8.8	109	29	3.8	127	48	2.6	23332	2014	11.6
Nov 20/23	10.9	83	18	4.6	150	19	7.9	7602	981	7.7
Nov 23/27	24.0	112	26	4.3	198	33	6.0	22101	2797	7.9
	24.0	123	13	9.5	329	43	7.7	155665	9288	16.8
	24.0	106	28	3.8	199	27	7.4	2302	584	3.9
	22.7	102	30	3.4	156	16	9.8	3894	931	4.2
Nov 27/30	24.0	82	19	4.3	120	23	5.2	35337	3077	11.5
	24.0	108	15	7.2	115	27	4.3	19097	8513	2.2
	22.1	138	14	9.9	228	15	15.2	1943	710	2.7
Nov 30/04	20.2	102	12	8.5	104	17	6.1	68777	20667	3.3
Dec 04/07	24.0	113	23	4.9	93	27	3.4	2036	805	2.5
	24.0	105	29	3.6	59	18	3.3	4115	760	5.4
	21.8	109	11	9.9	61	17	3.6	21232	2023	10.5
Dec 07/11	20.0	106	17	6.2	78	14	5.6	5222	520	10.0
	20.0	82	24	3.4	86	28	3.1	5127	1214	4.2
	20.0	94	11	8.5	88	25	3.5	887	422	2.1
	20.0	124	16	7.8	51	15	3.4	535	16947	-31.7
	13.0	39	10	3.9	39	14	2.8	602	19808	-32.9
TOTAL	890.9	9247	1972	4.7	4649	1116	4.2	561343	398748	1.4

TABLE 7.5

RAINFALL / WIND DATA
NOVEMBER - DECEMBER 1987

DATE	NOVEMBER RAIN INCHES	NOVEMBER WIND MPH	DATE	DECEMBER RAIN INCHES	DECEMBER WIND MPH
1	-	-	1	-	-
2	-	-	2	0.02	24.0
3	-	24.5	3	-	[illegible]
4	-	26.0	4	-	46.0
5	-	26.0	5	0.04	23.5
6	0.18	-	6	0.44	22.0
7	0.10	21.0	7	0.43	-
8	0.02	23.5	8	-	39.5
9	-	27.5	9	-	26.0
10	-	-	10	-	-
11	-	-	11	-	35.5
12	-	22.0	12	-	40.5
13	-	-	13	-	-
14	-	-	14	0.51	44.0
15	0.36	46.0	15	1.59	42.0
16	0.66	32.0			
17	-	33.5			
18	-	20.0			
19	-	37.0			
20	-	30.5			
21	-	-			
22	-	31.5			
23	0.04	27.0			
24	1.75	21.0			
25	0.03	21.0			
26	0.12	22.0			
27	0.62	-			
28	0.08	25.5			
29	-	27.5			
30	0.02	26.5			

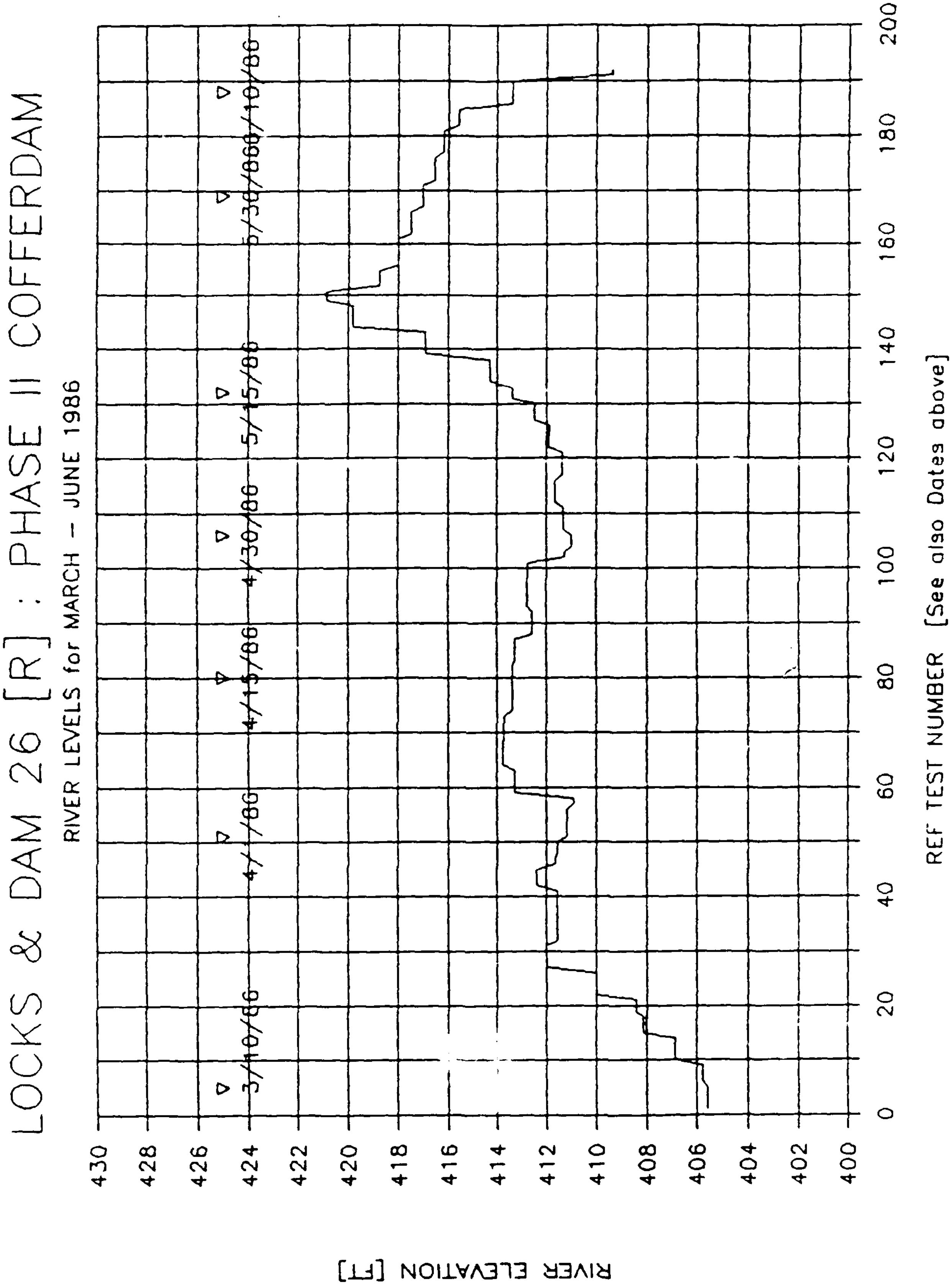


FIG 7.1 RIVER ELEVATIONS MARCH-JUNE 1986

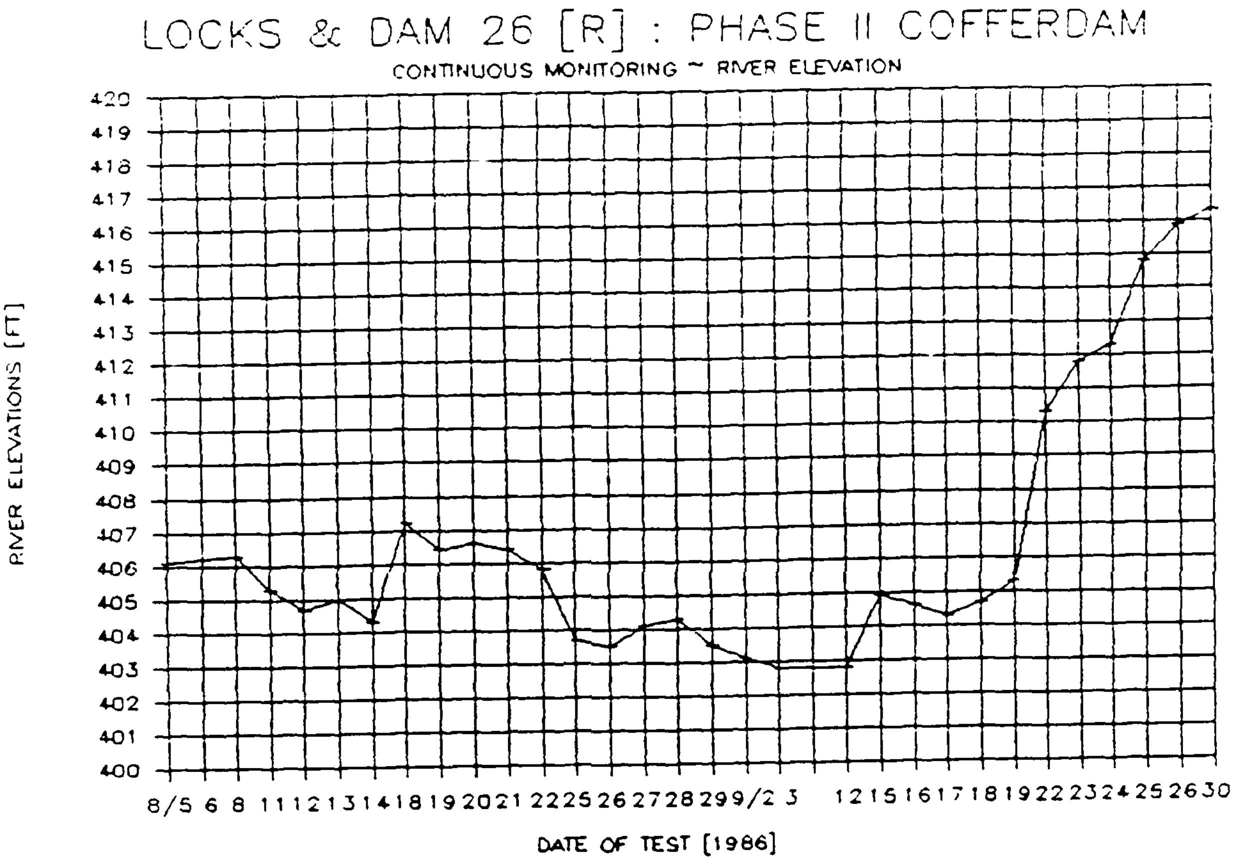


FIG 7.2 RIVER ELEVATIONS AUGUST-SEPTEMBER 1986

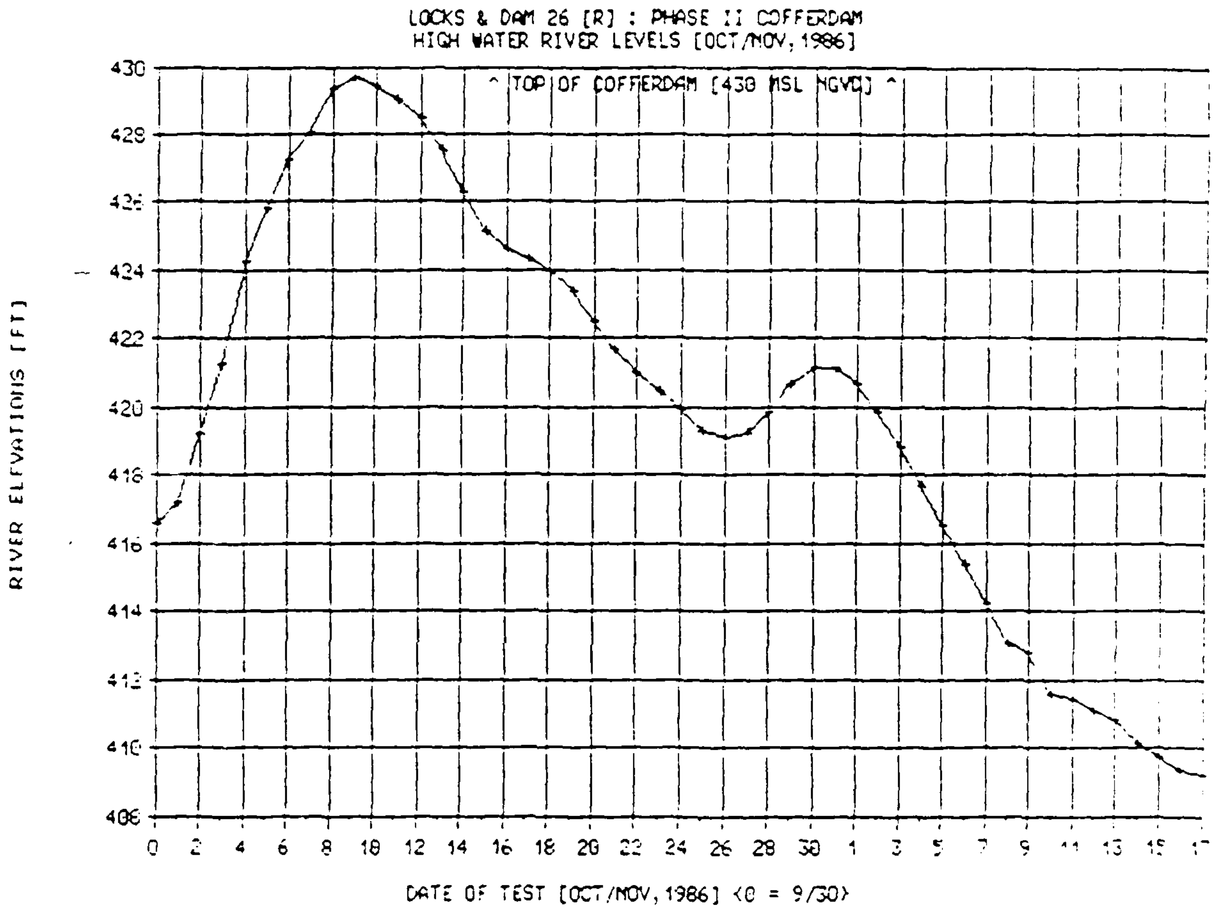


FIG 7.3 RIVER ELEVATIONS OCTOBER-NOVEMBER 1986

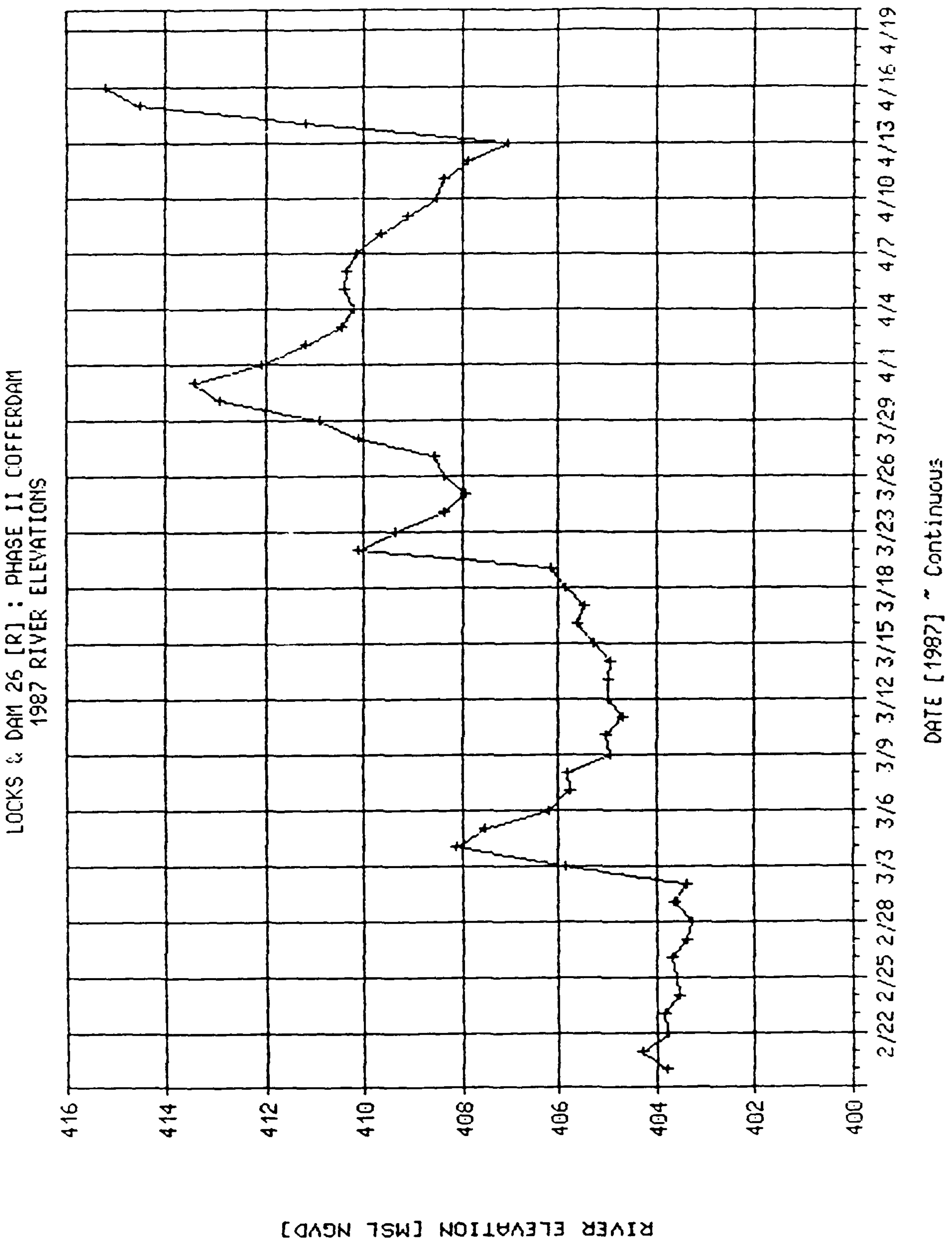


FIG 7.4 RIVER ELEVATIONS FEBRUARY-APRIL 1987

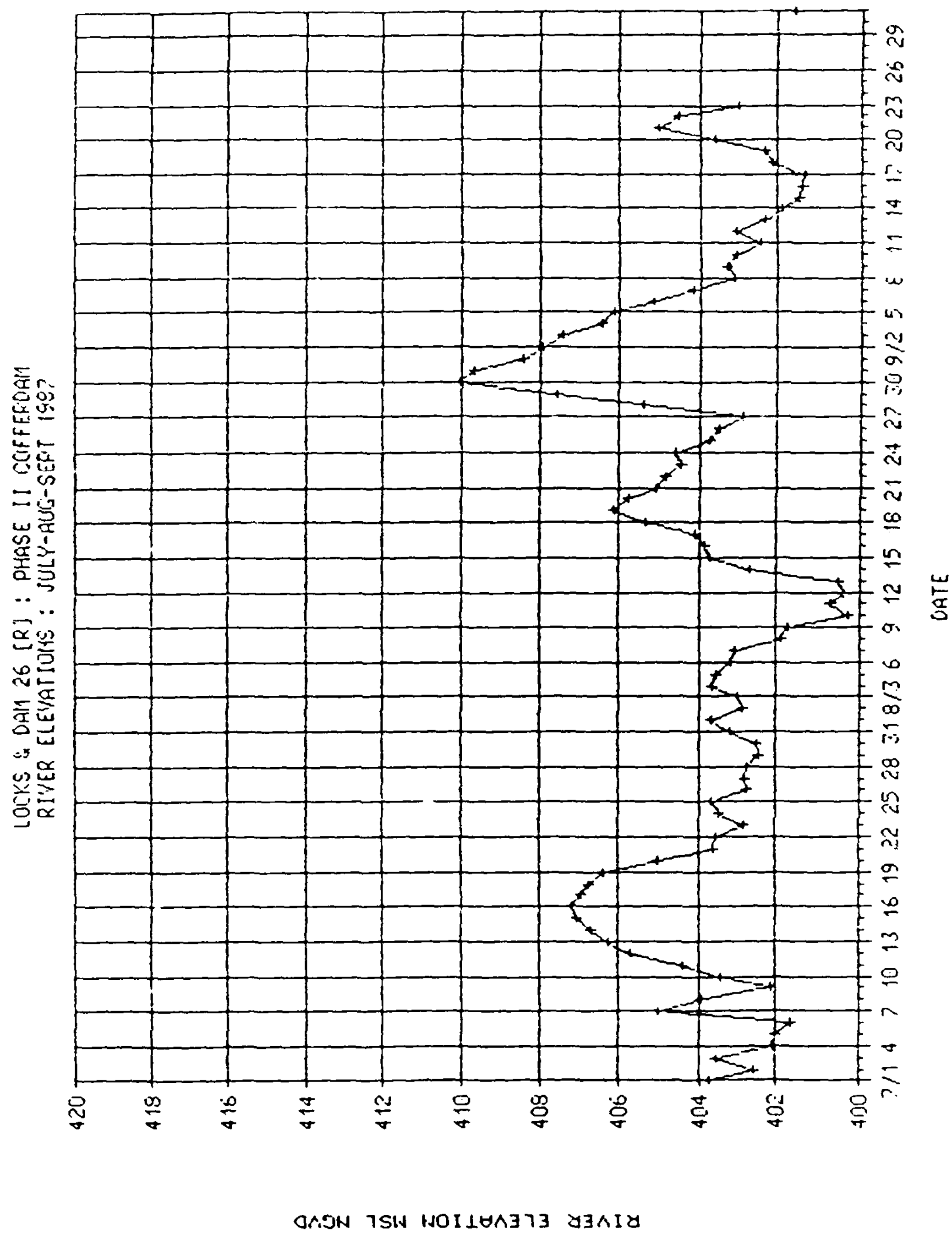


FIG 7.5 RIVER ELEVATIONS JULY-SEPTEMBER 1987

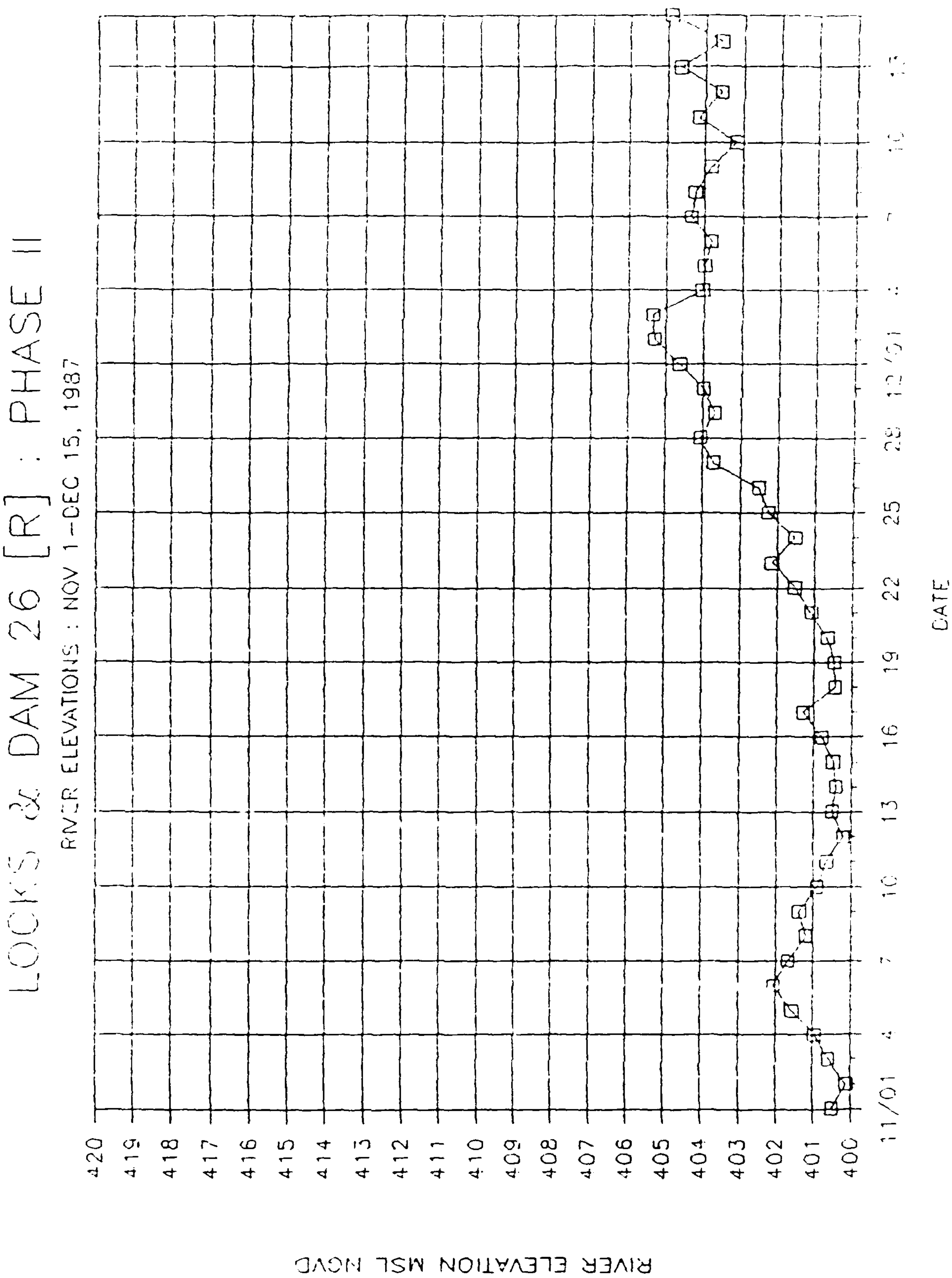


FIG 7.6 RIVER ELEVATIONS NOVEMBER-DECEMBER 1987

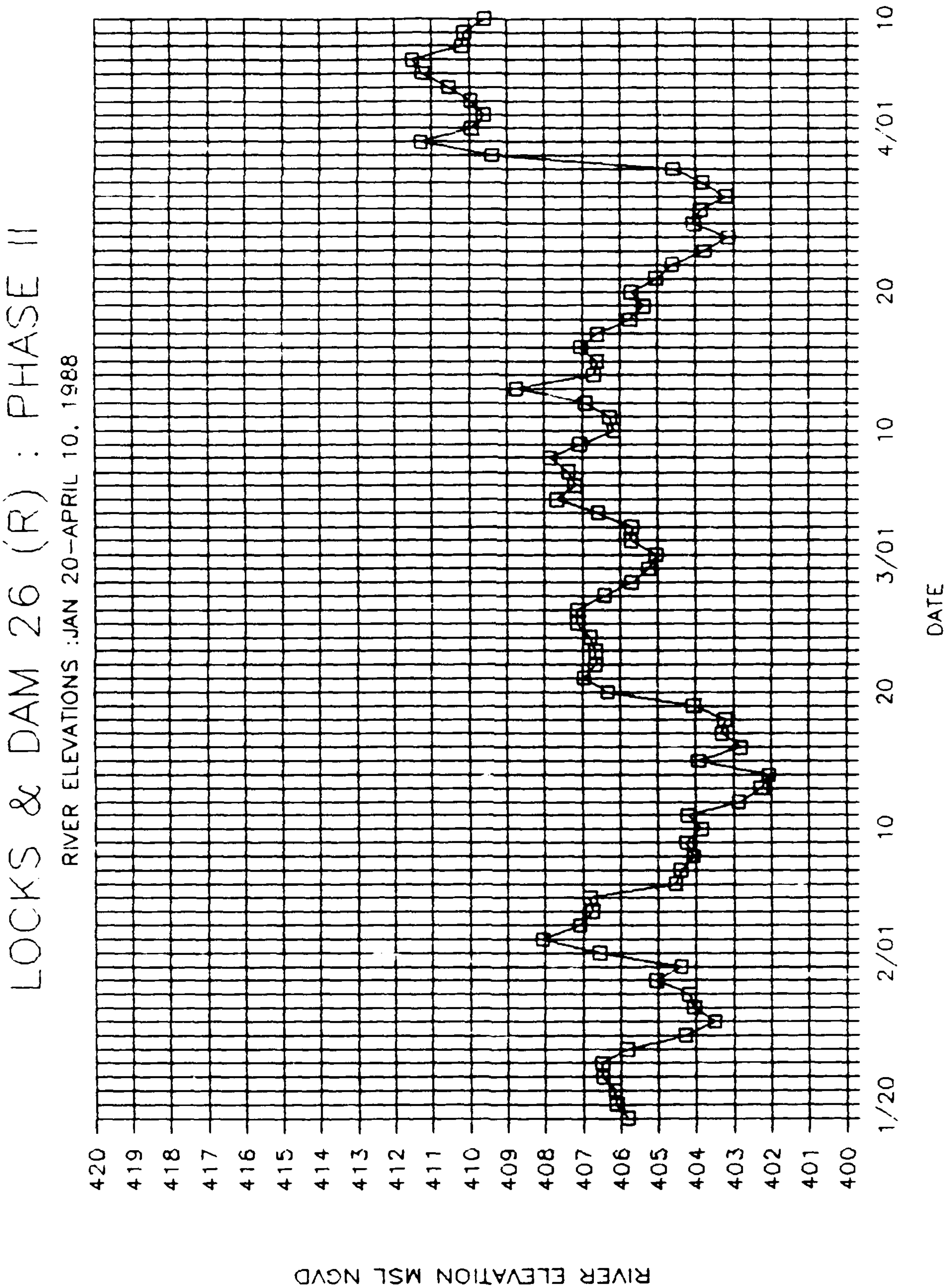
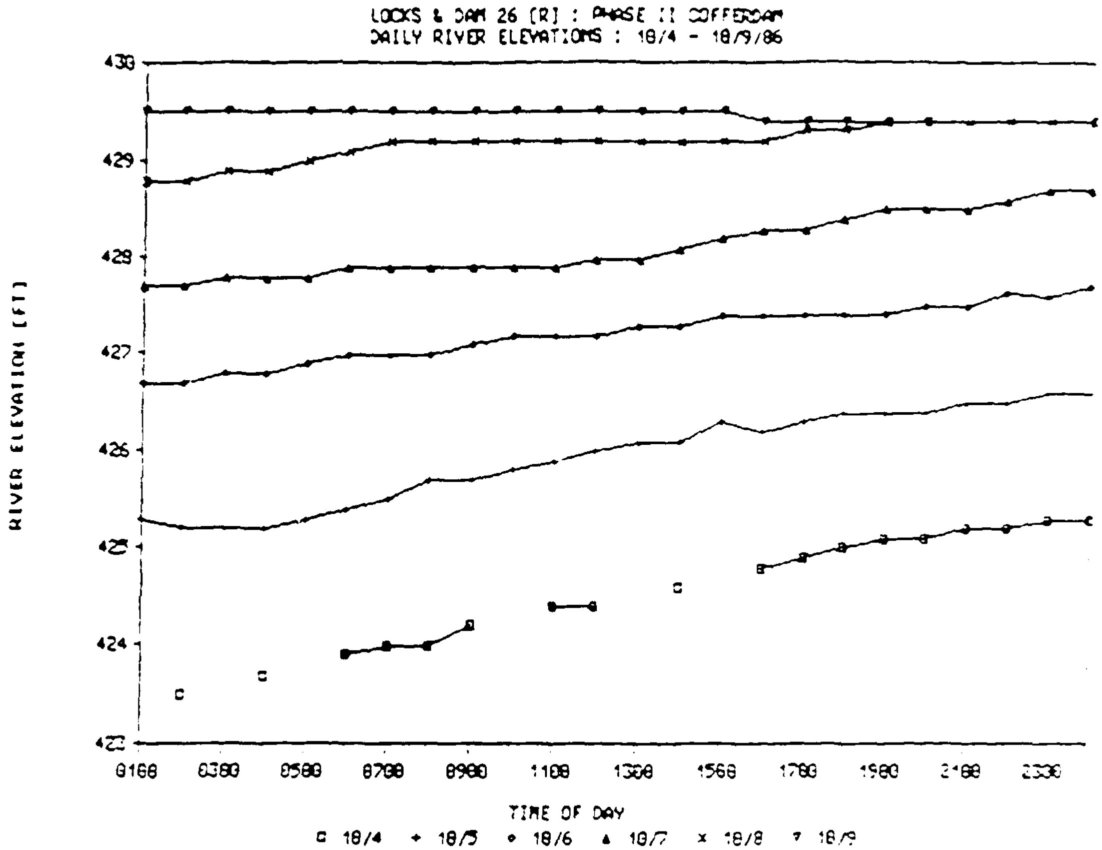


FIG 7.7 RIVER ELEVATIONS JANUARY-APRIL 1988



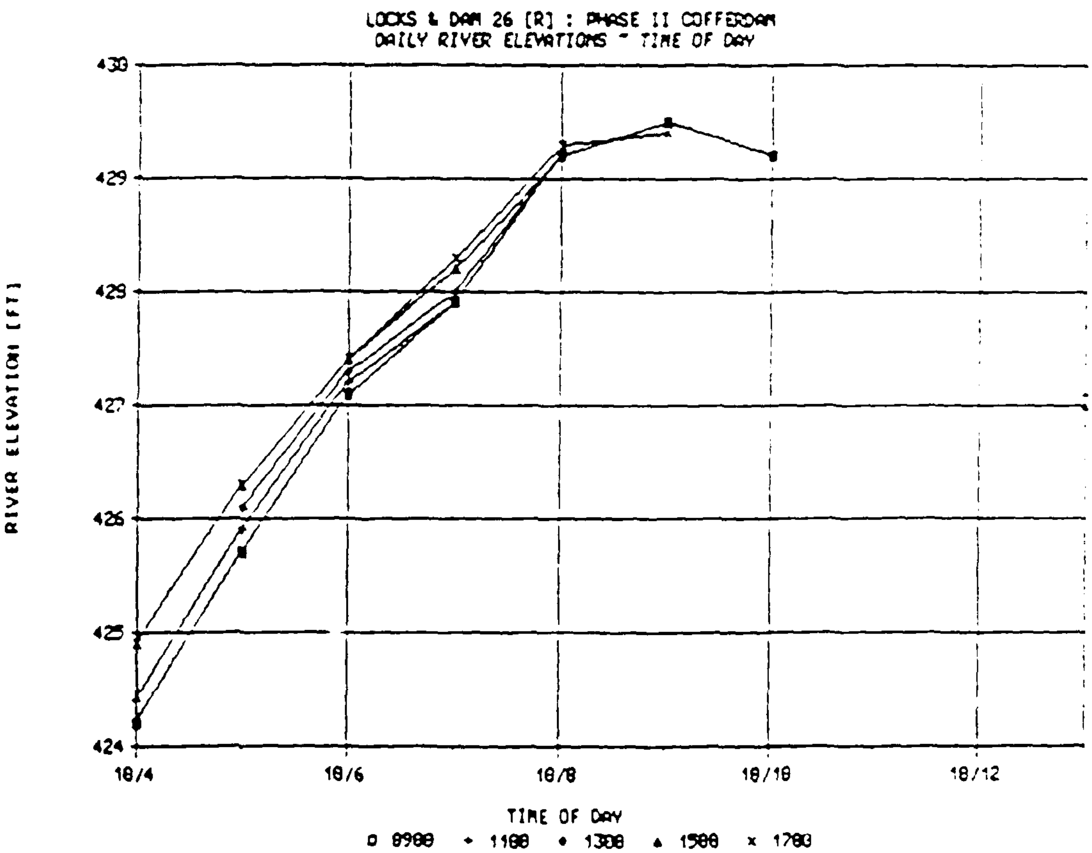


FIG 7.8 RIVER ELEVATIONS VS TIME OF DAY; 10/4-10/9, 1986

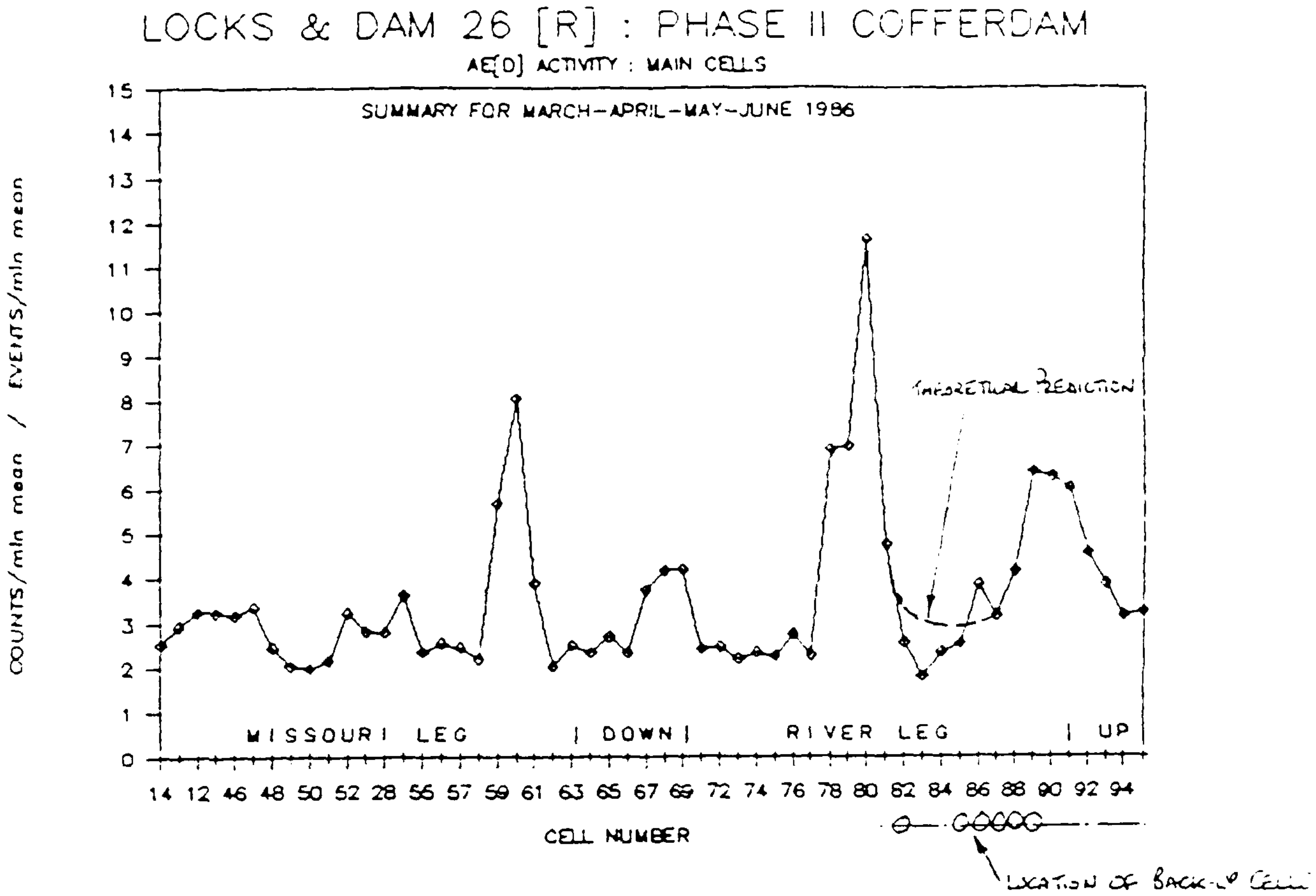


FIG 7.9 AE ACTIVITY SUMMARY OF MEAN VALUES: MAIN CELLS; MARCH-JUNE 1986

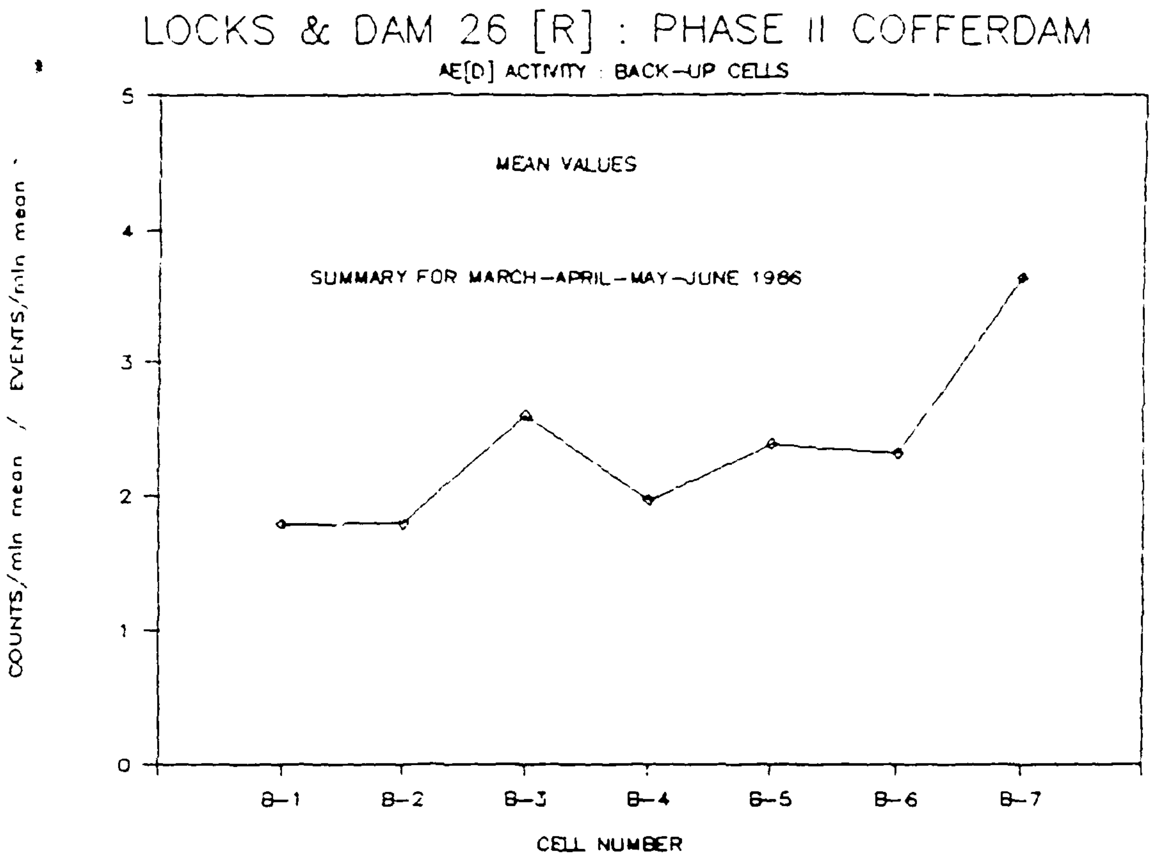


FIG 7.10 AE ACTIVITY SUMMARY OF MEANS VALUES: BACK-UP CELLS; MARCH-JUNE 1986

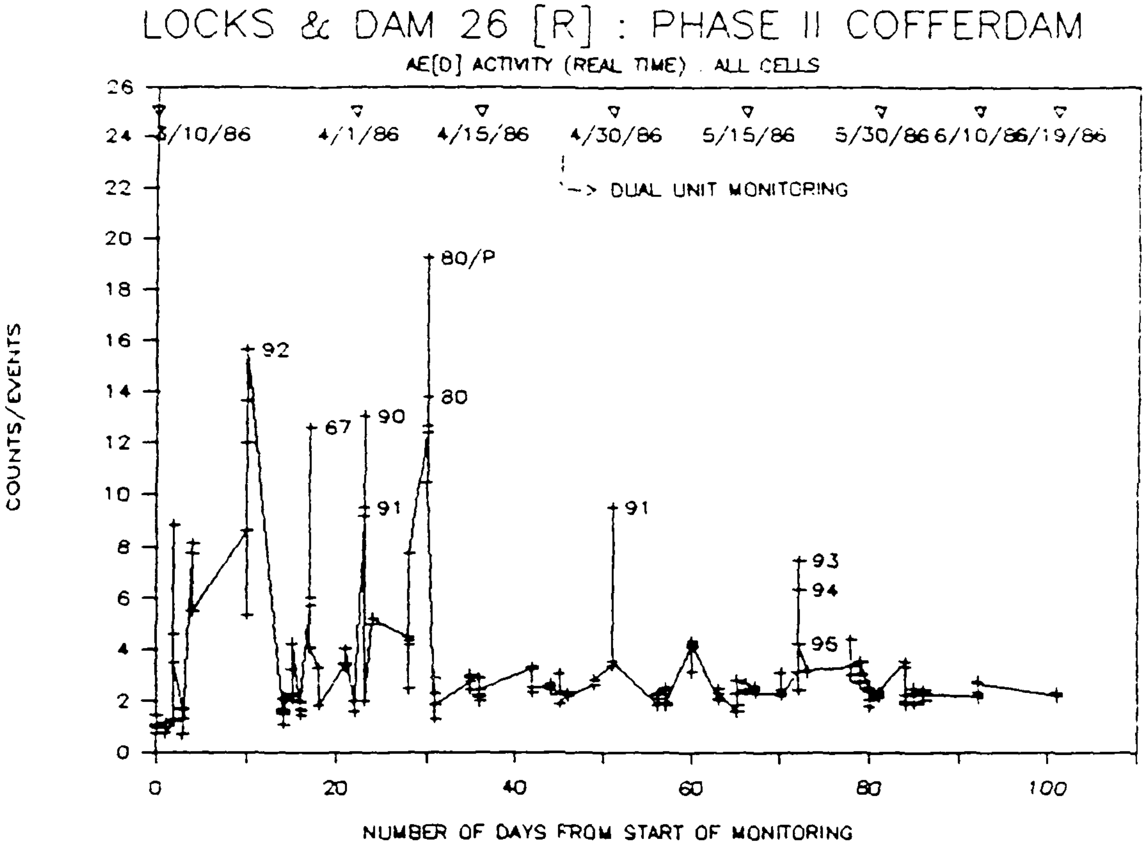


FIG 7.11 AE ACTIVITY: ALL CELLS; MARCH-JUNE 1986

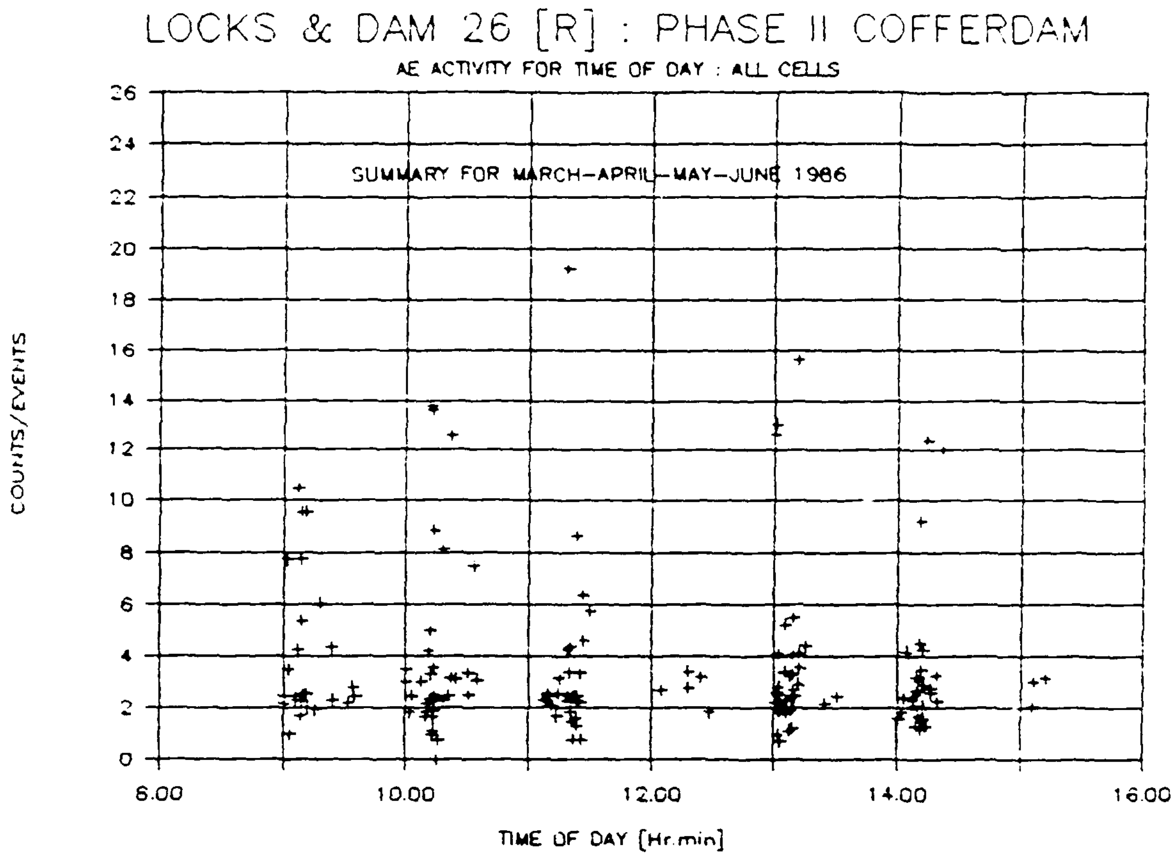


FIG 7.12 AE ACTIVITY VS TIME OF DAY: ALL CELLS; MARCH-JUNE 1986

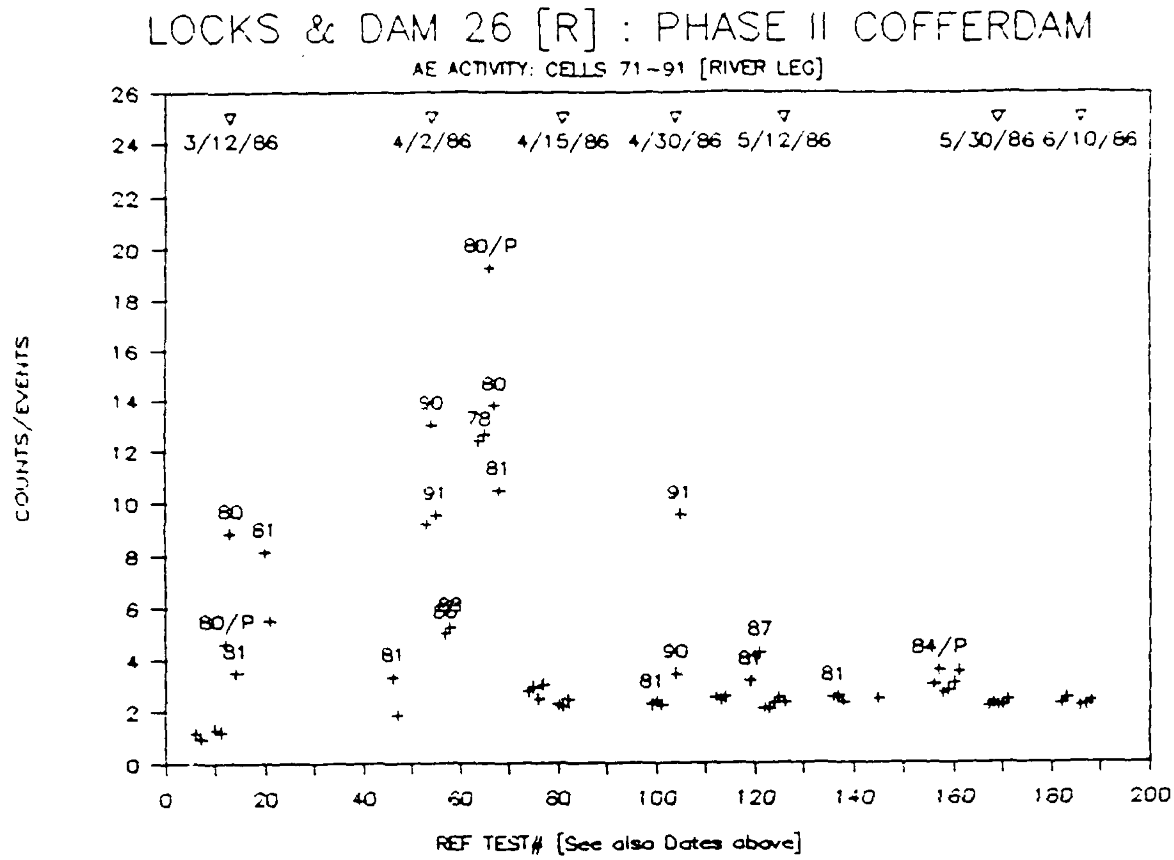


FIG 7.13 AE ACTIVITY: RIVER LEG (CELLS 71-91) MARCH-JUNE 1986

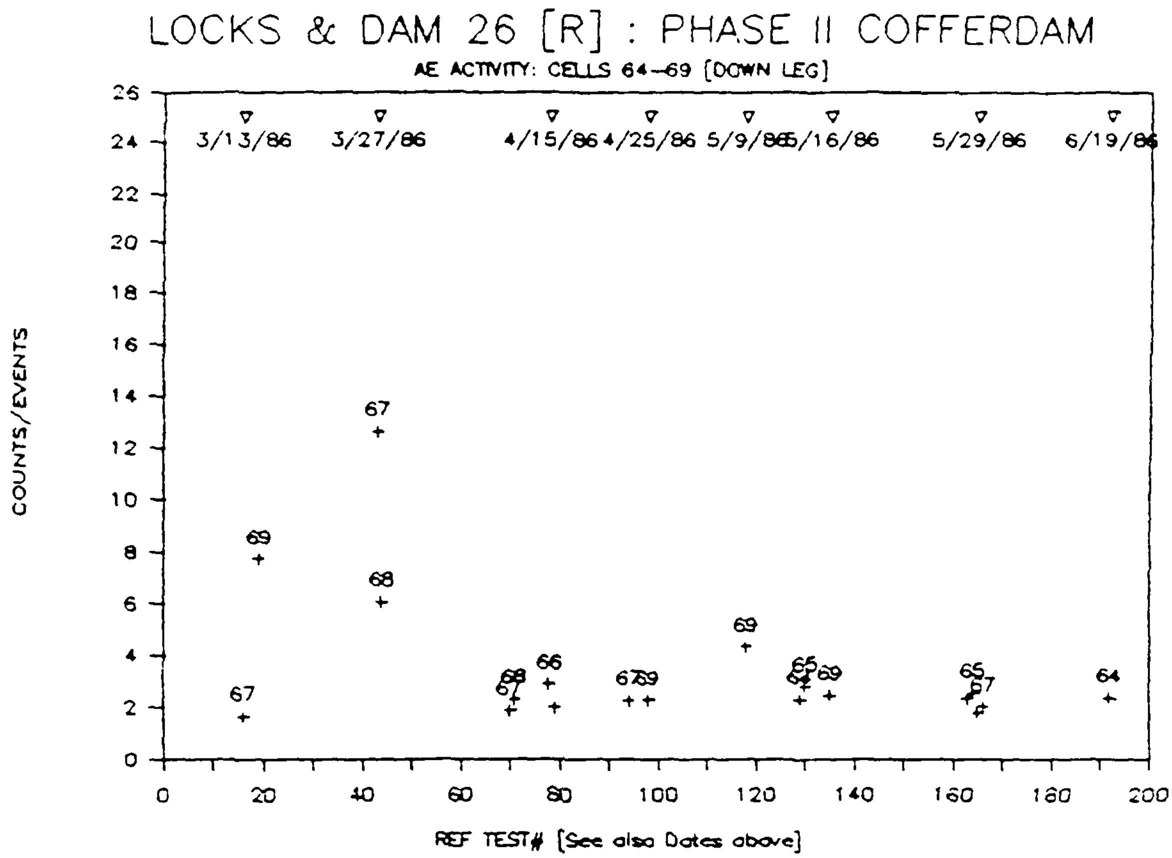


FIG 7.14 AE ACTIVITY: DOWNSTREAM LEG (CELLS 64-69) MARCH-JUNE 1986

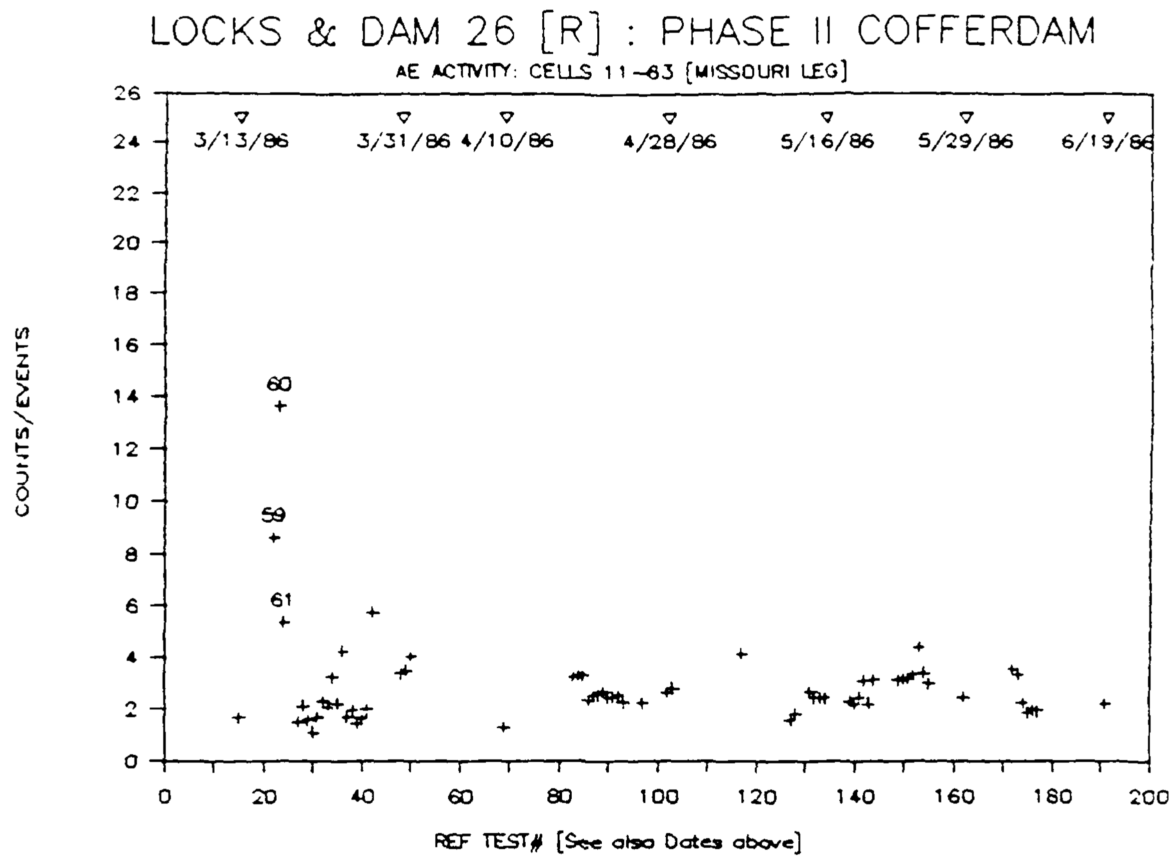


FIG 7.15 AE ACTIVITY: MISSOURI LEG (CELLS 11-63) MARCH-JUNE 1986

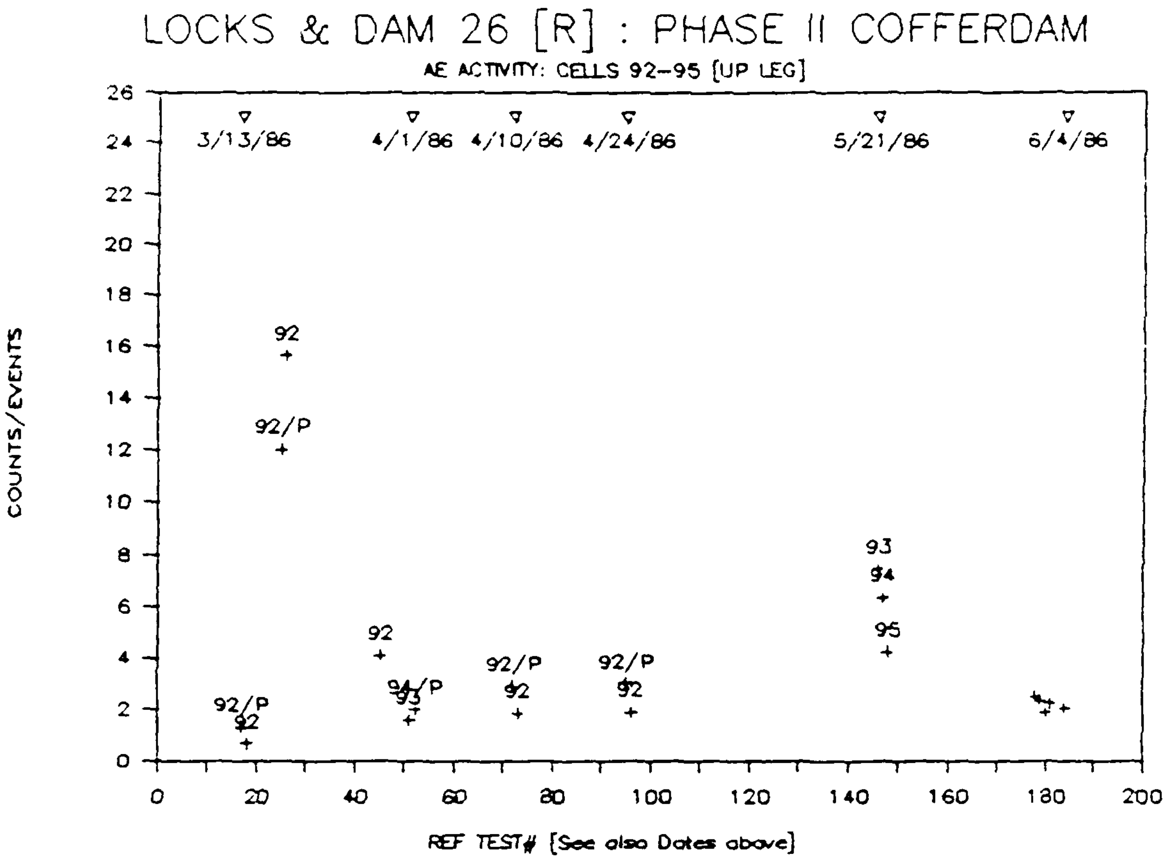


FIG 7.16 AE ACTIVITY: UPSTREAM LEG (CELLS 92-95) MARCH-JUNE 1986

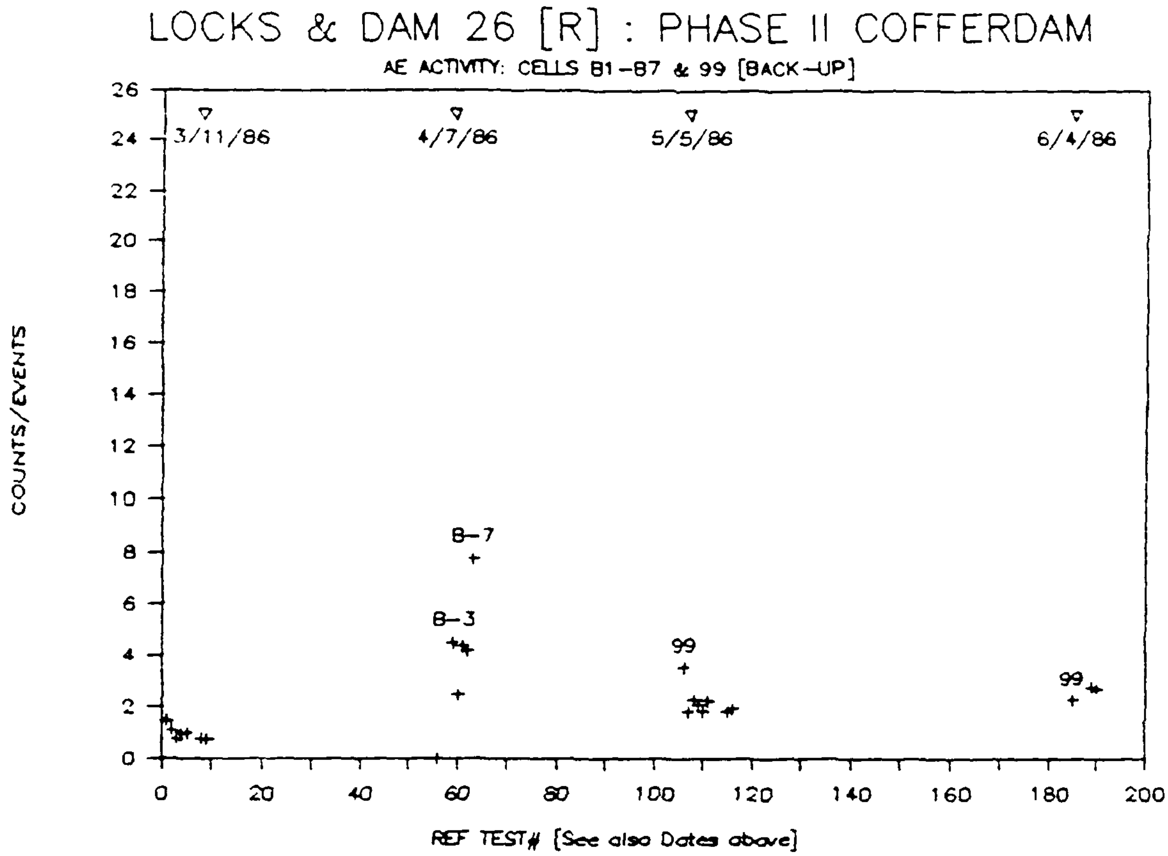
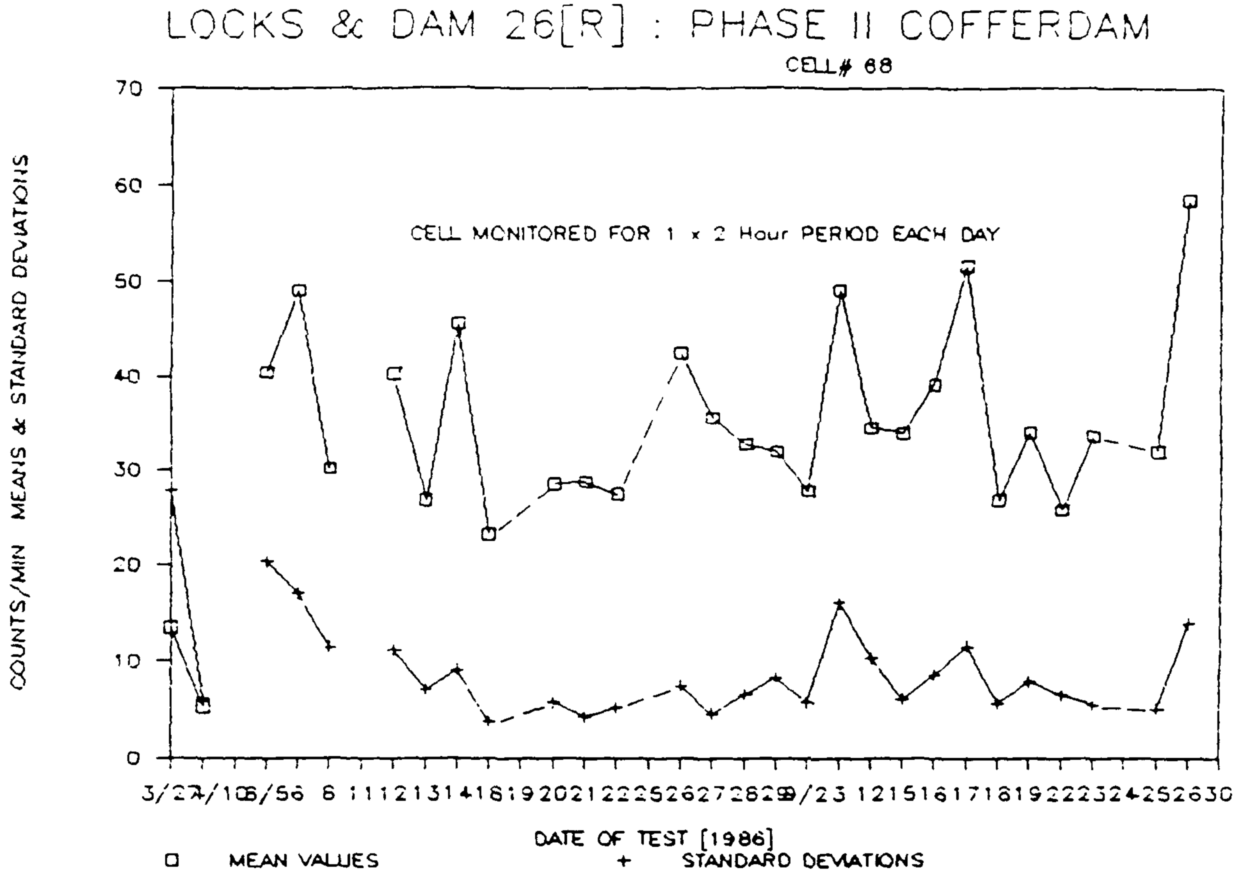


FIG 7.17 AE ACTIVITY: BACK-UP AND THIRD STAGE TIE-IN CELLS; MARCH-JUNE 1986



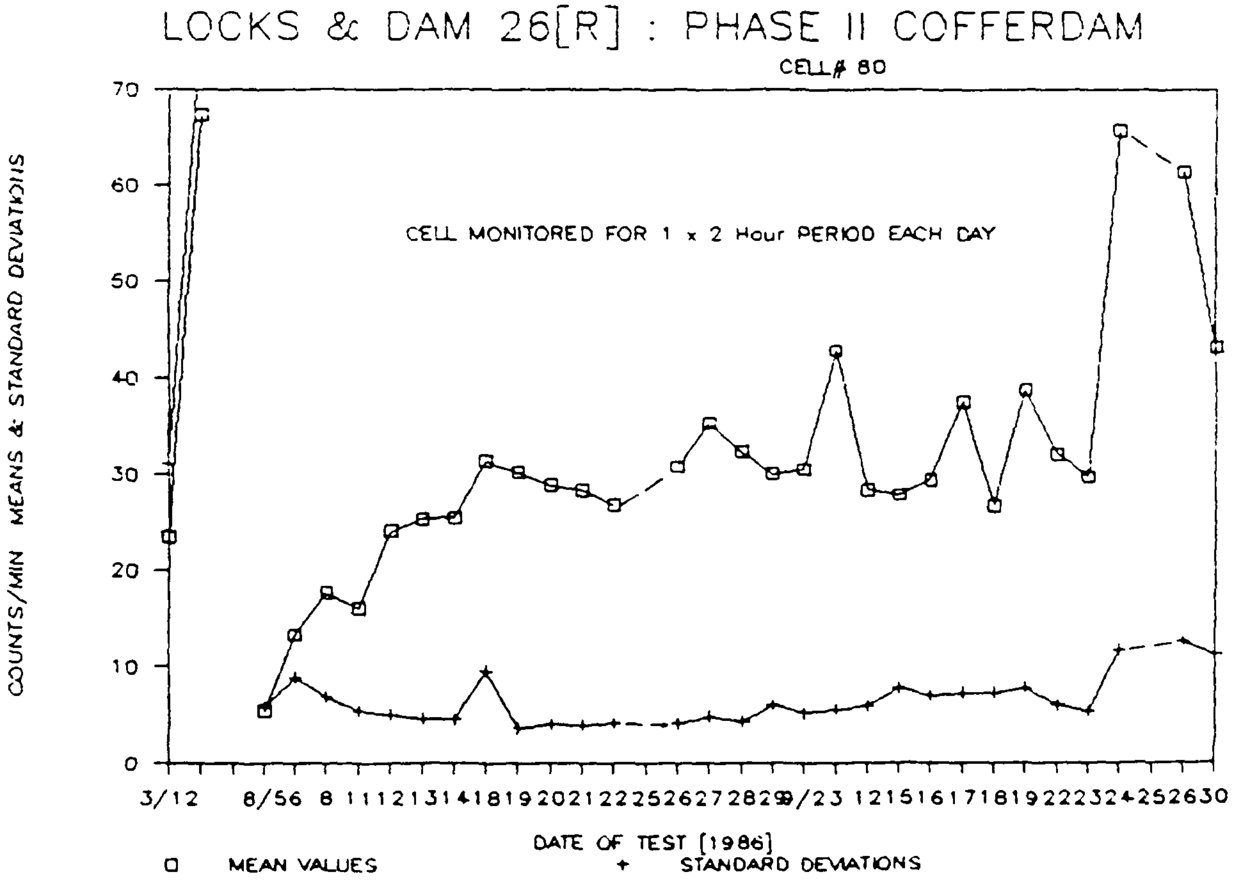


FIG 7.18 AE ACTIVITY (CELLS 68 & 80) MARCH-JUNE 1986

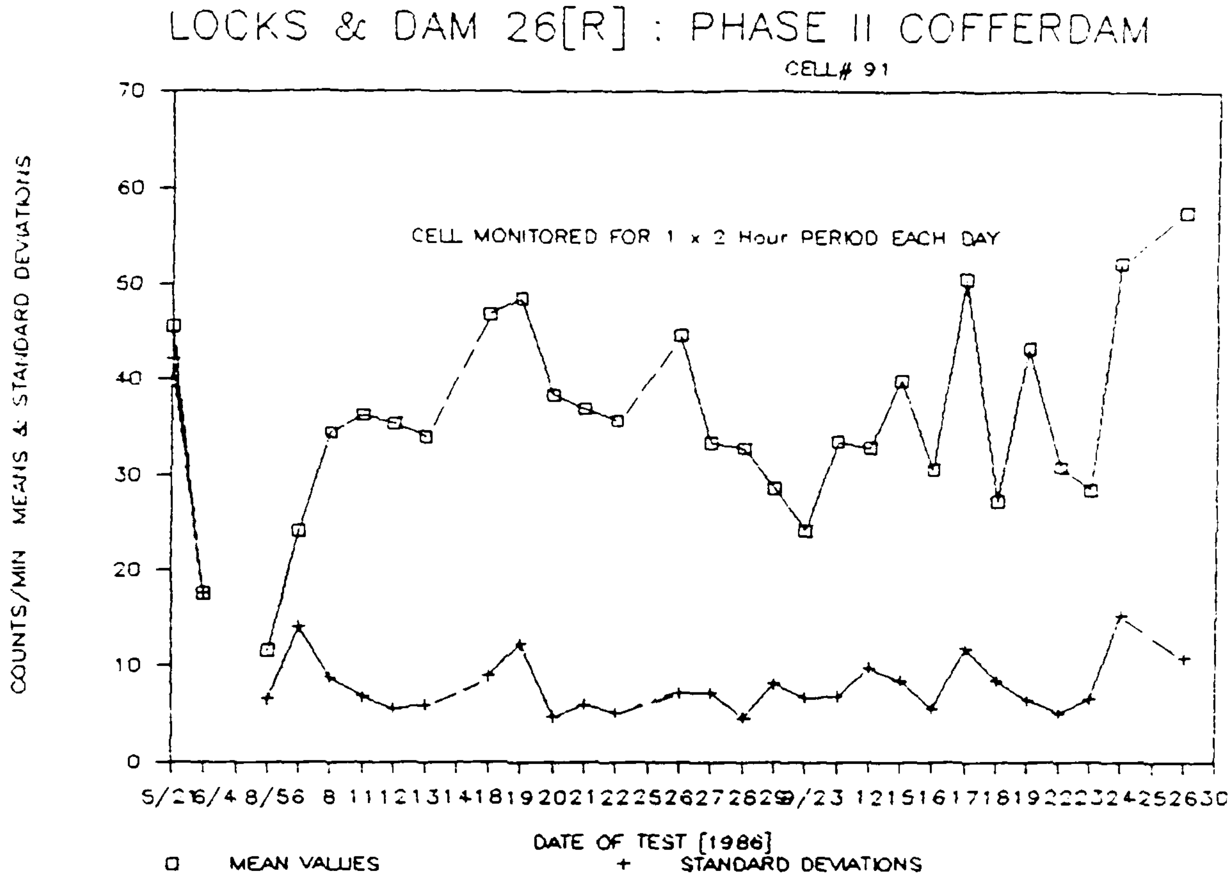
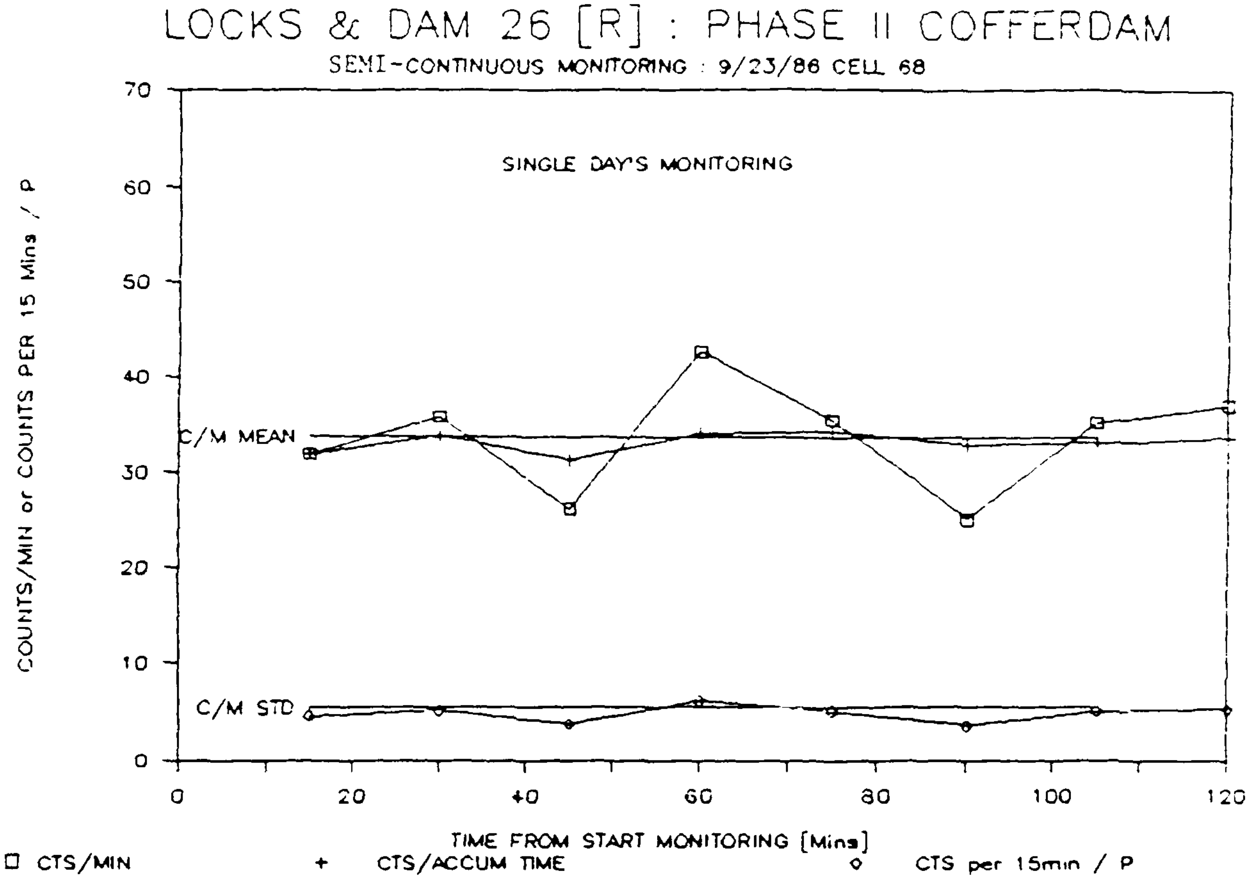


FIG 7.19 AE ACTIVITY (CELL 91) MARCH-JUNE 1986



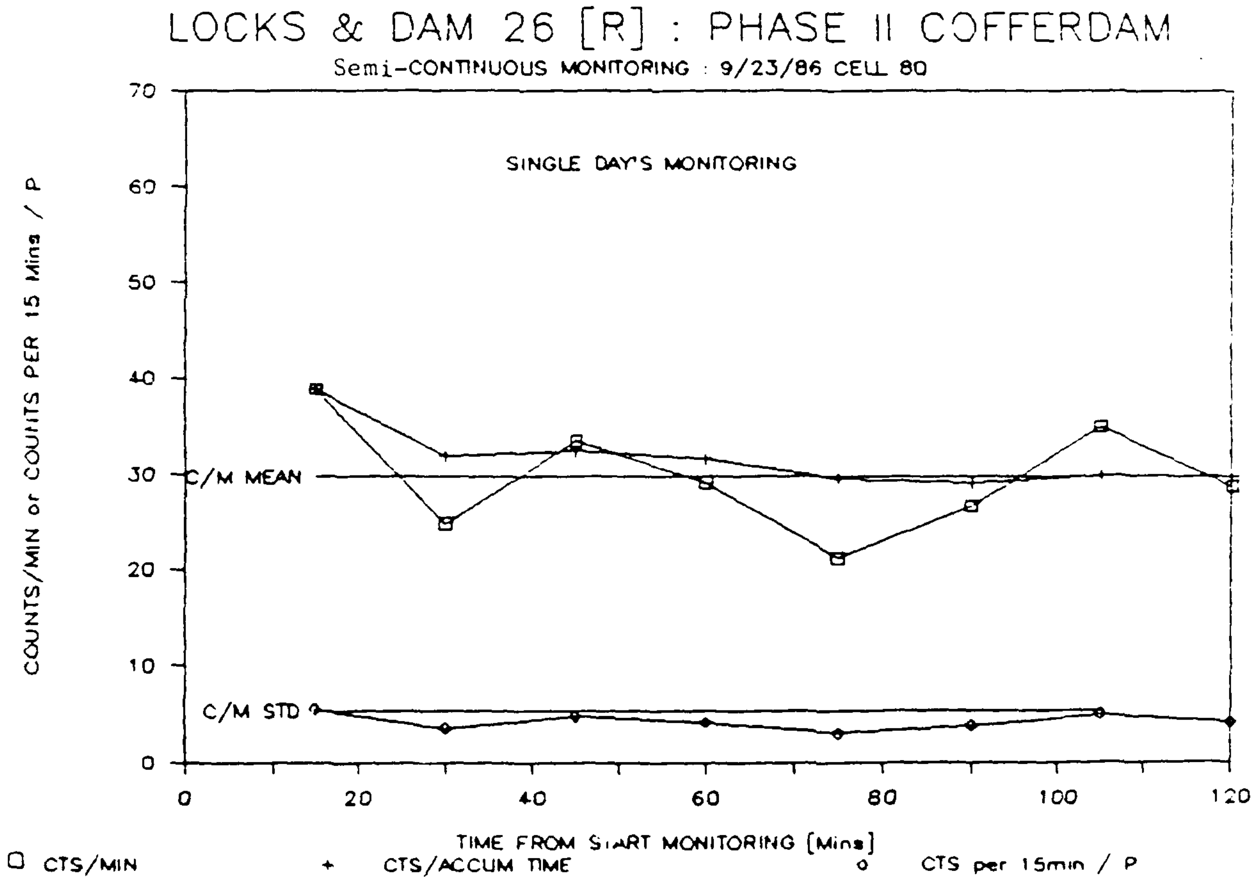


FIG 7.20 SEMI-CONTINUOUS MONITORING: 9/23/86 (CELLS 68 & 80)

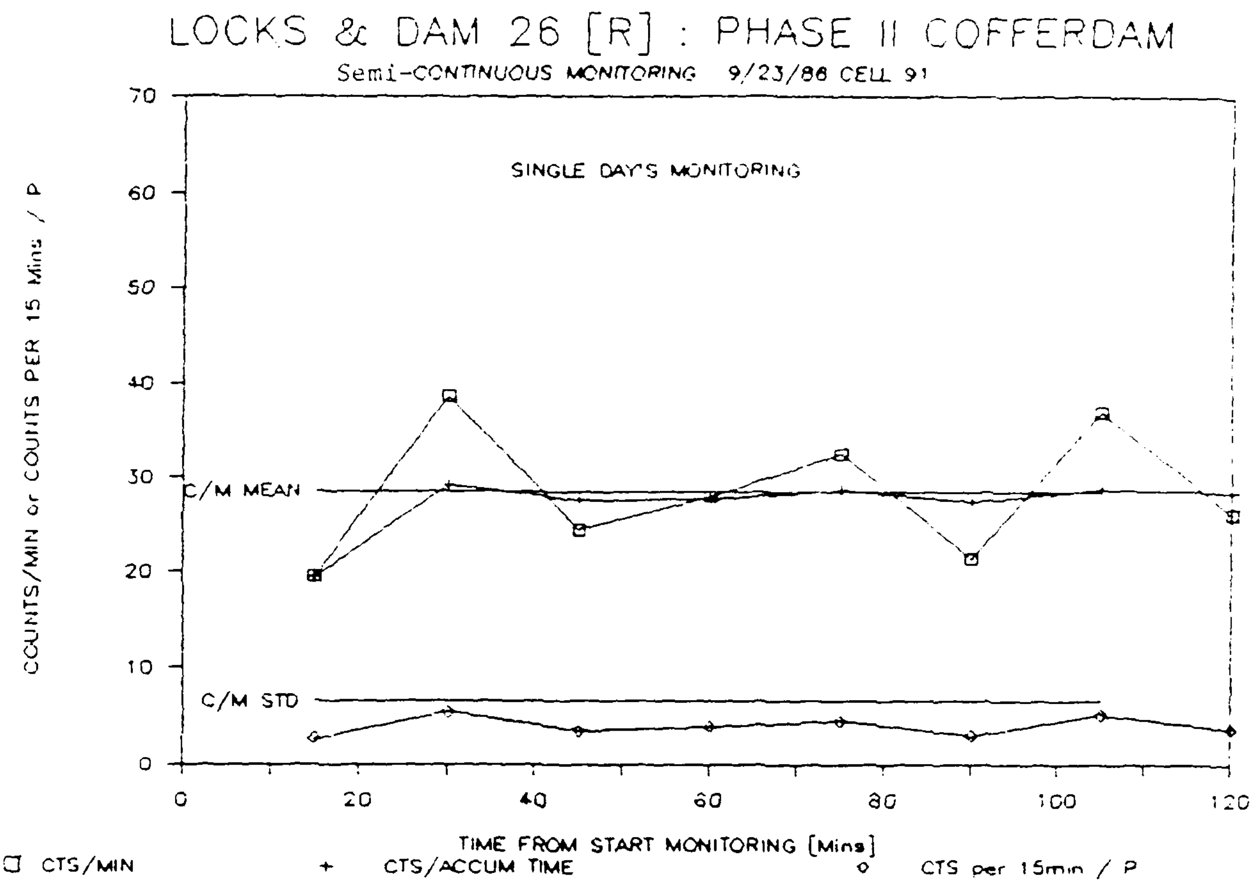
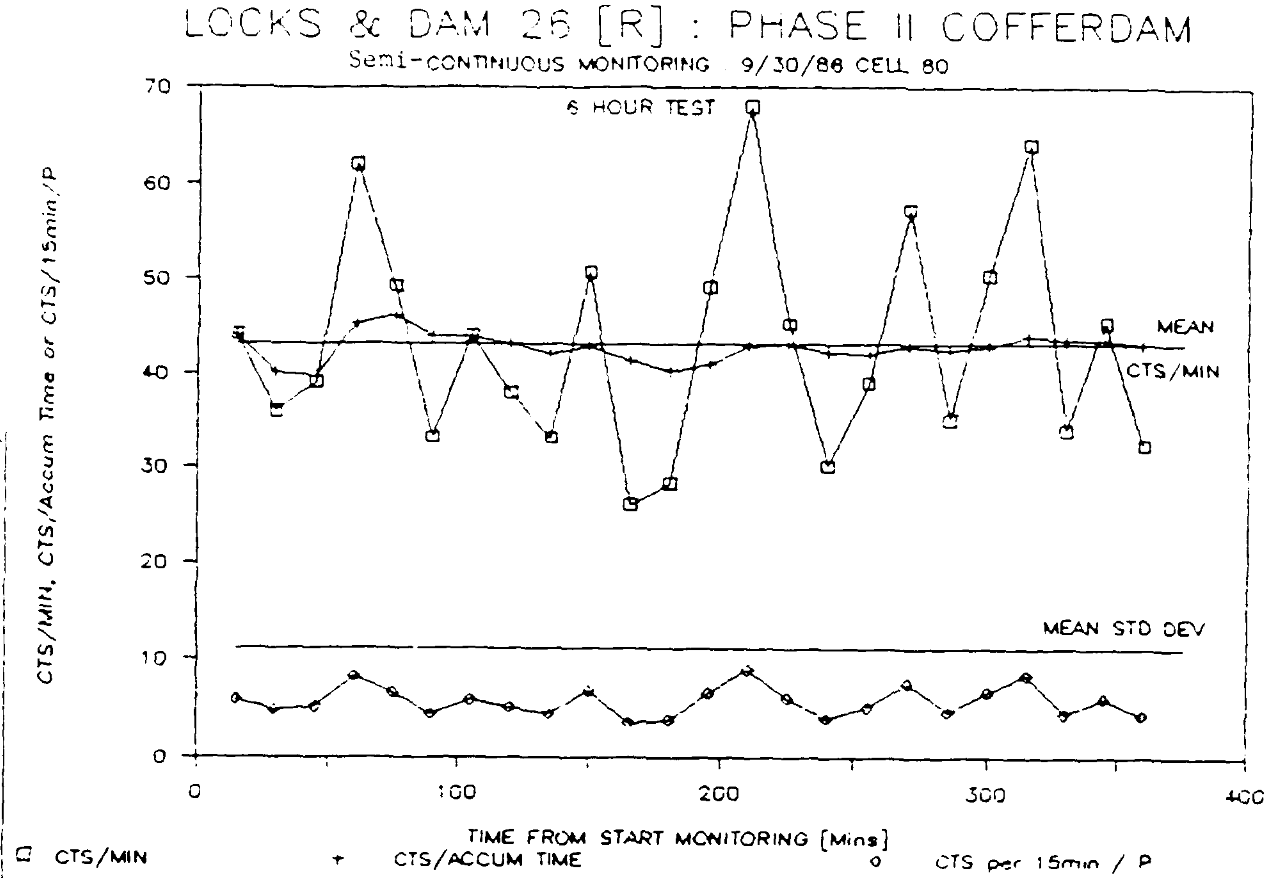
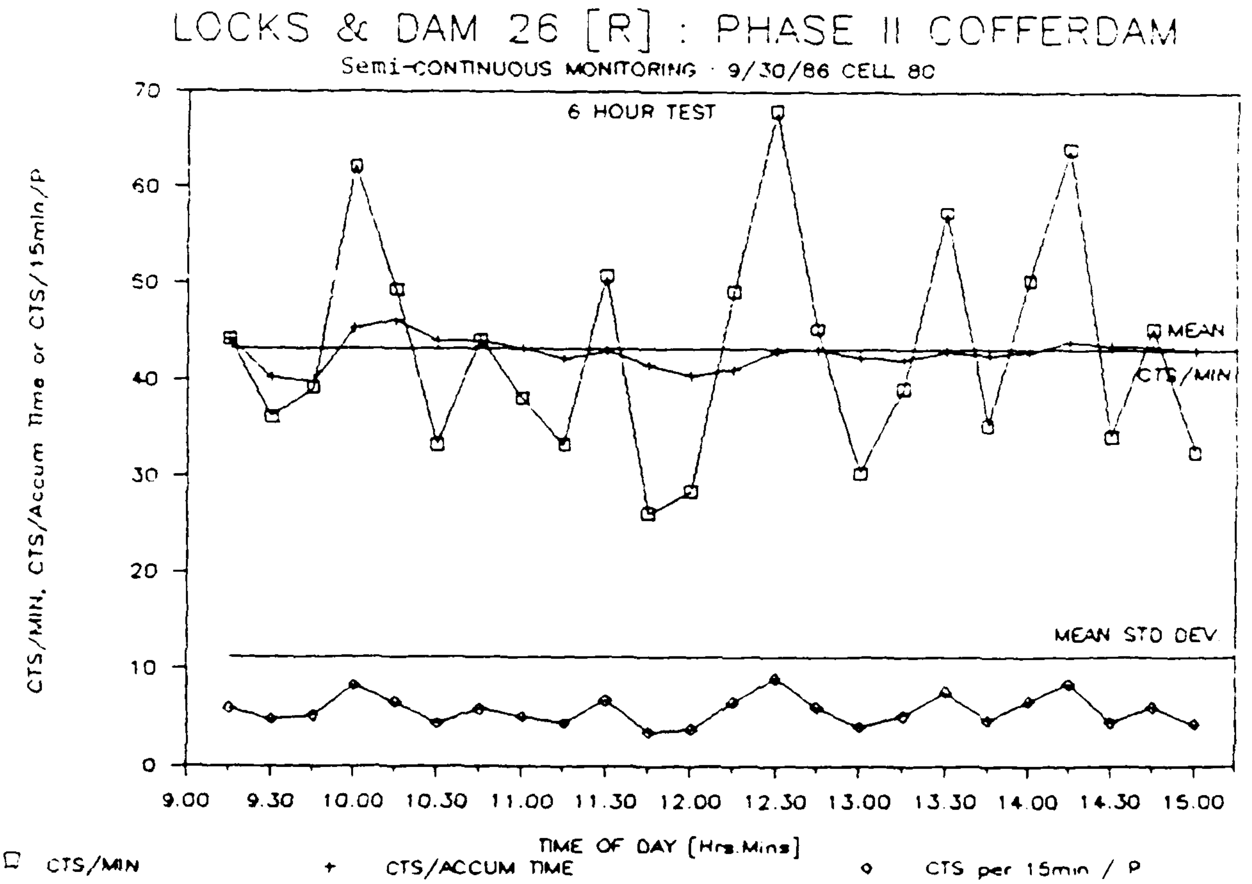


FIG 7.21 SEMI-CONTINUOUS MONITORING: 9/23/86 (CELL 91)

FIG 7.22 SEMI-CONTINUOUS MONITORING 9/30/86 (CELL 80)





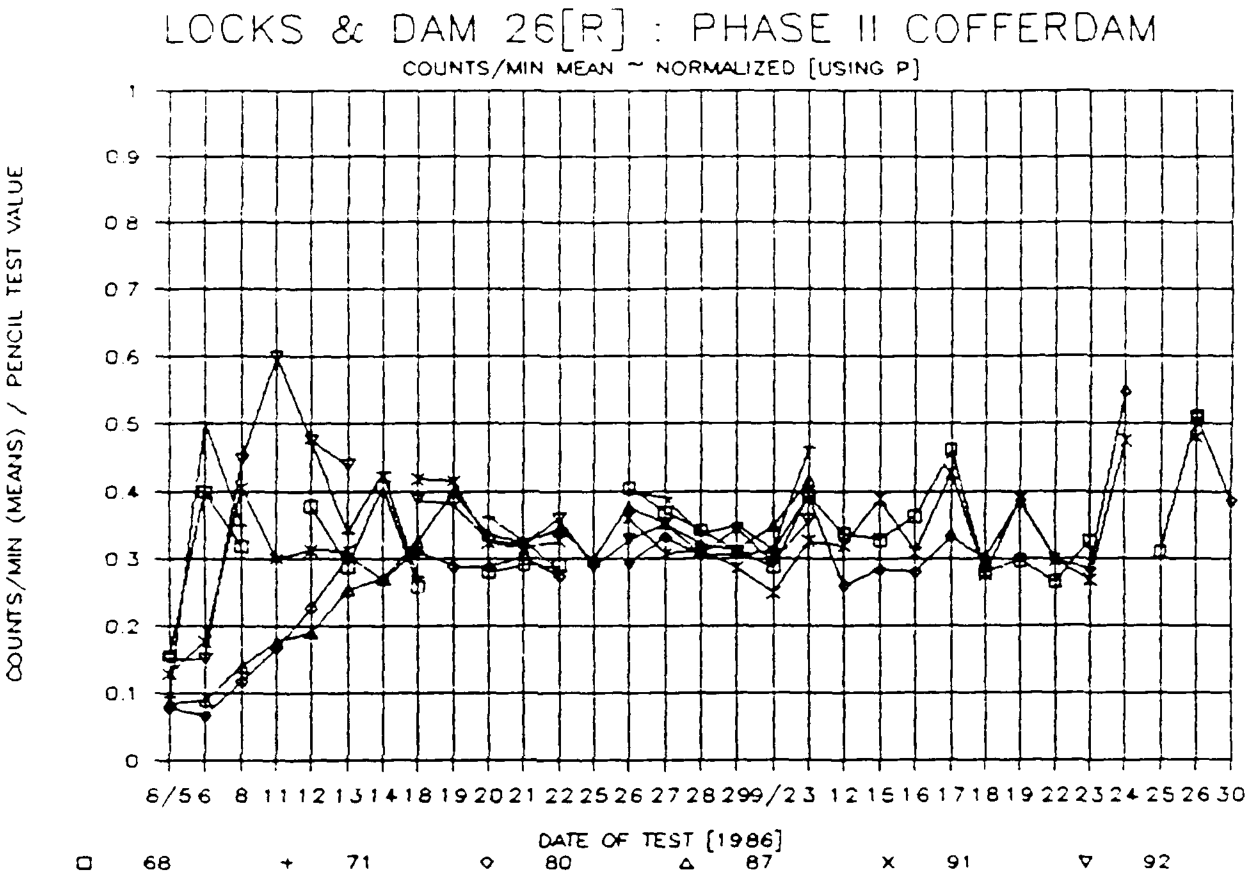


FIG 7.23 AE ACTIVITY:NORMALIZED (CELLS 68, 71, 80, 87, 91, 92)

AUGUST-SEPTEMBER 1986

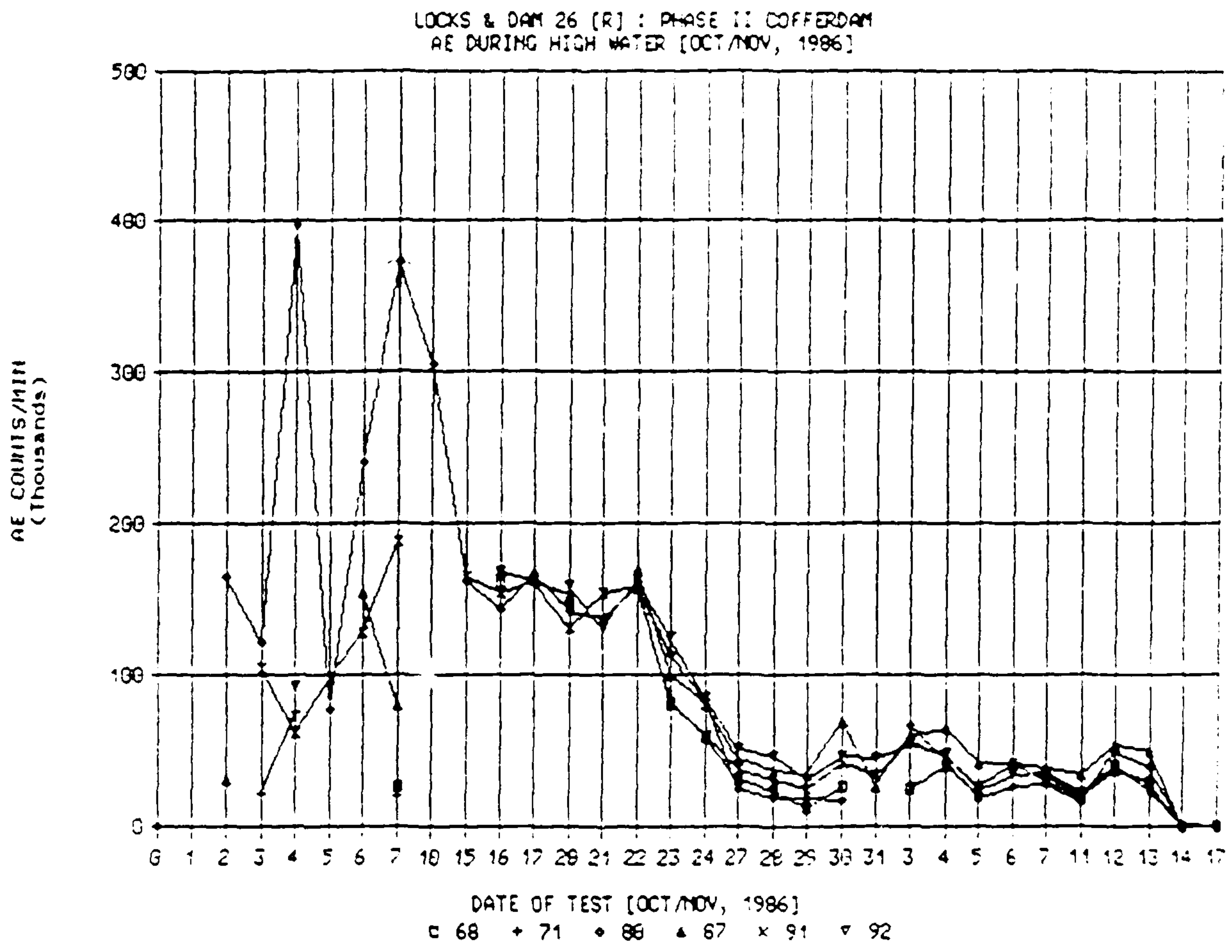
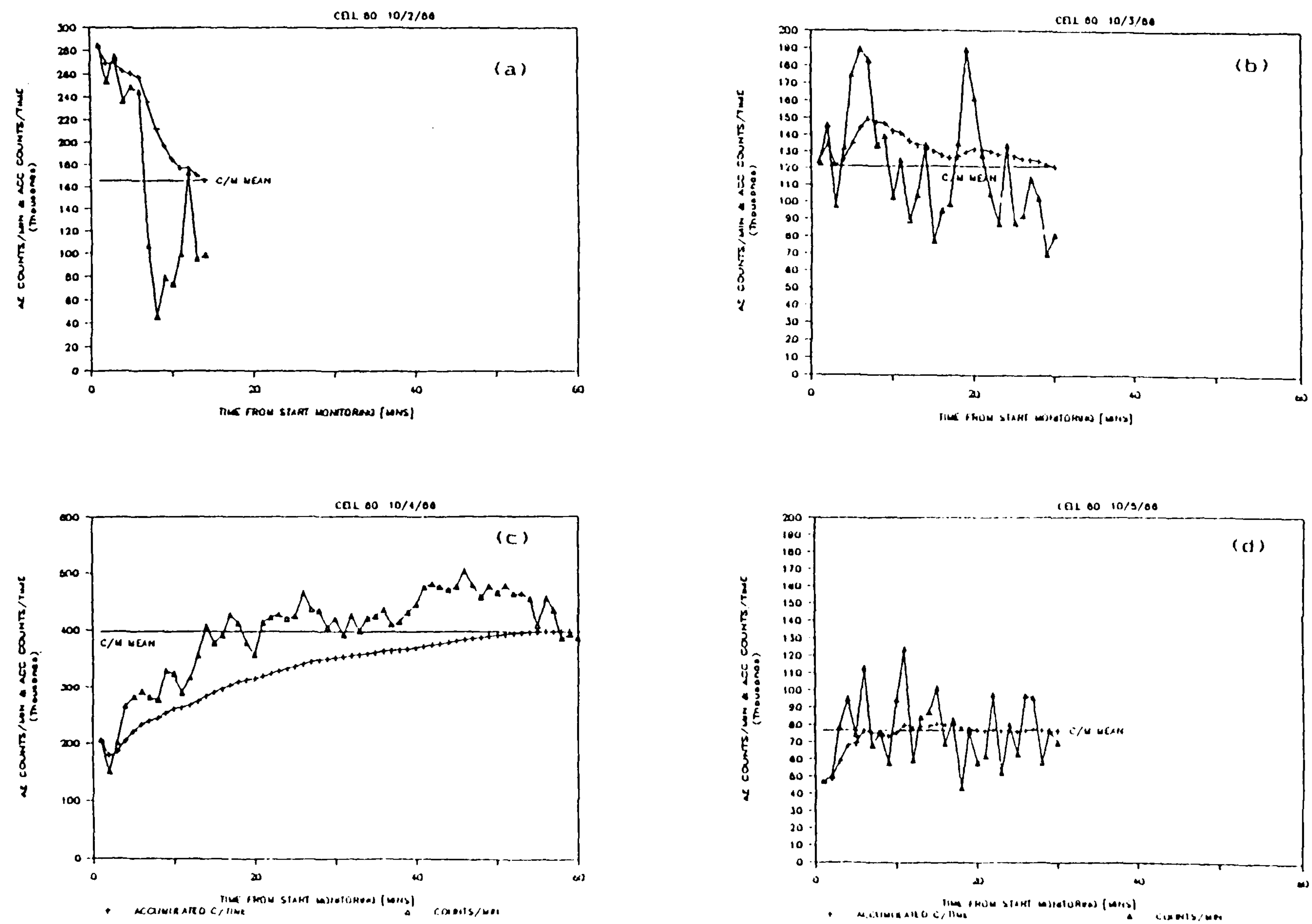


FIG 7.24 AE ACTIVITY:HIGH WATER (CELLS 68, 71, 80, 87, 91, 92);

OCTOBER-NOVEMBER 1986

FIG 7.25 TYPICAL AE MONITORING RECORDS: (CELL 80) OCTOBER 2-3-4-5, 1986

LOCKS & DAM 26 [R] : PHASE II COFFERDAM



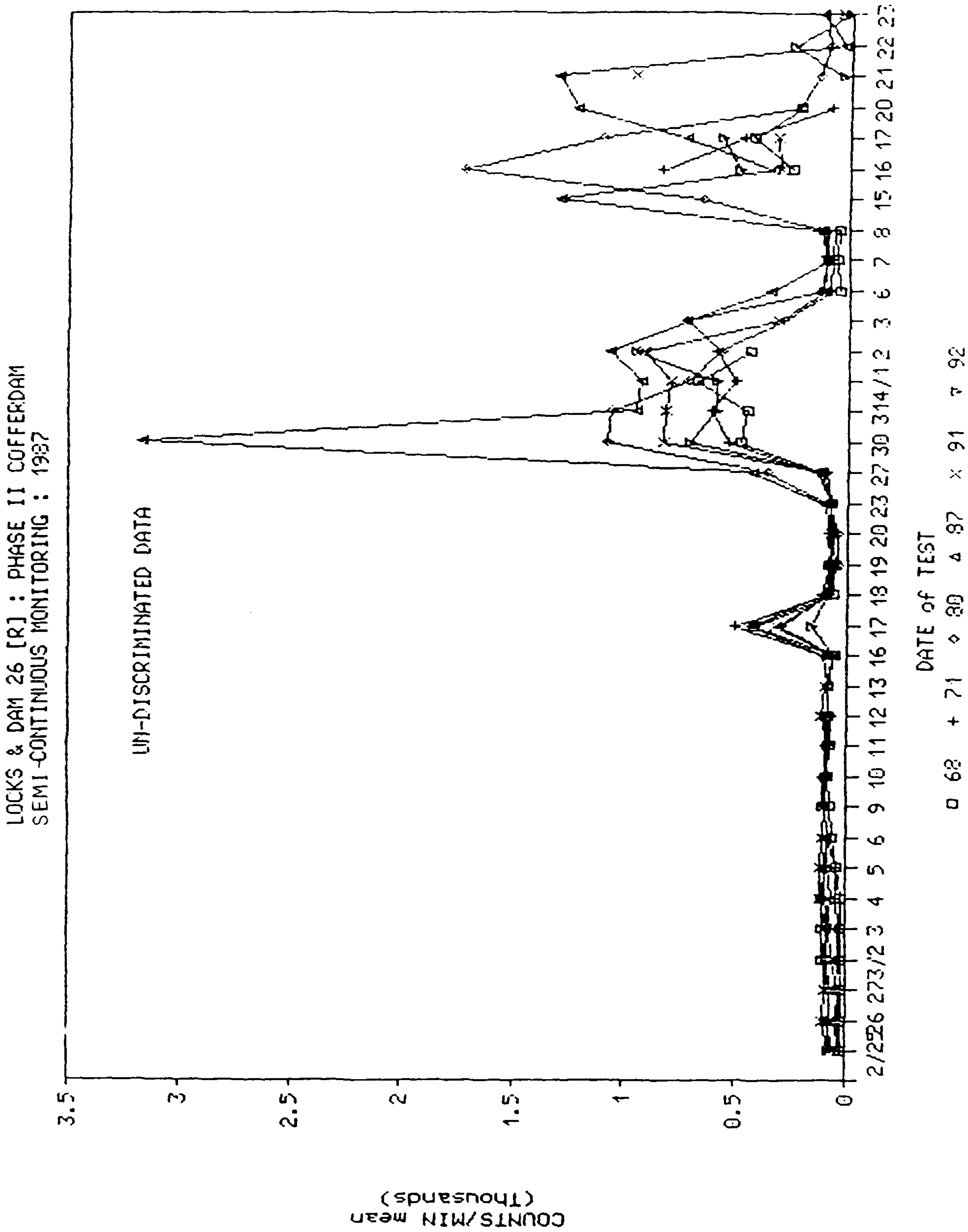


FIG 7.26 SEMI-CONTINUOUS MONITORING: UNDISCRIMINATED DATA

(CELLS 68, 71, 80, 87, 91, 92) FEBRUARY-APRIL 1987

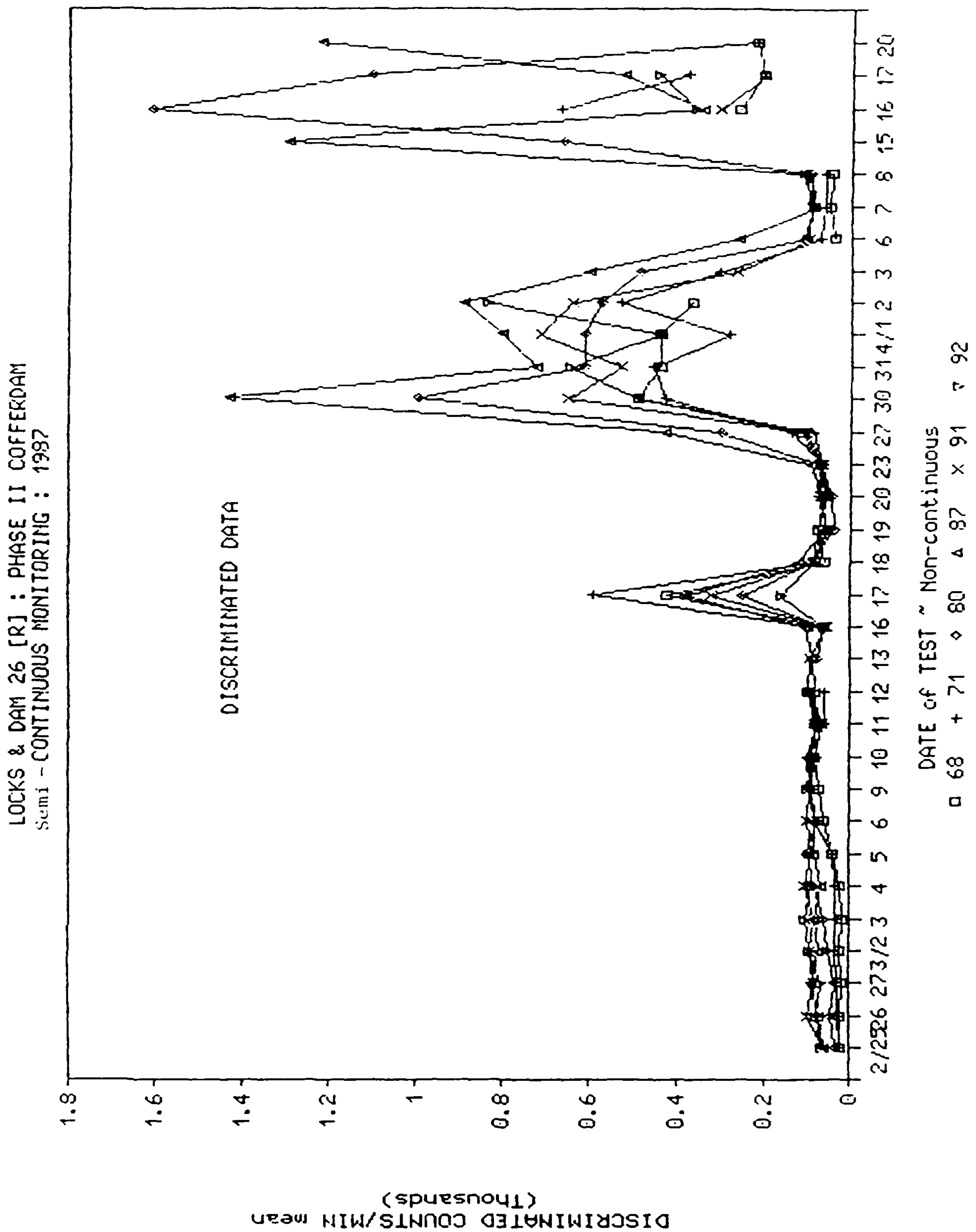


FIG 7.27 SEMI-CONTINUOUS MONITORING: DISCRIMINATED DATA

(CELLS 68, 71, 80, 87, 91, 92) FEBRUARY-APRIL 1987

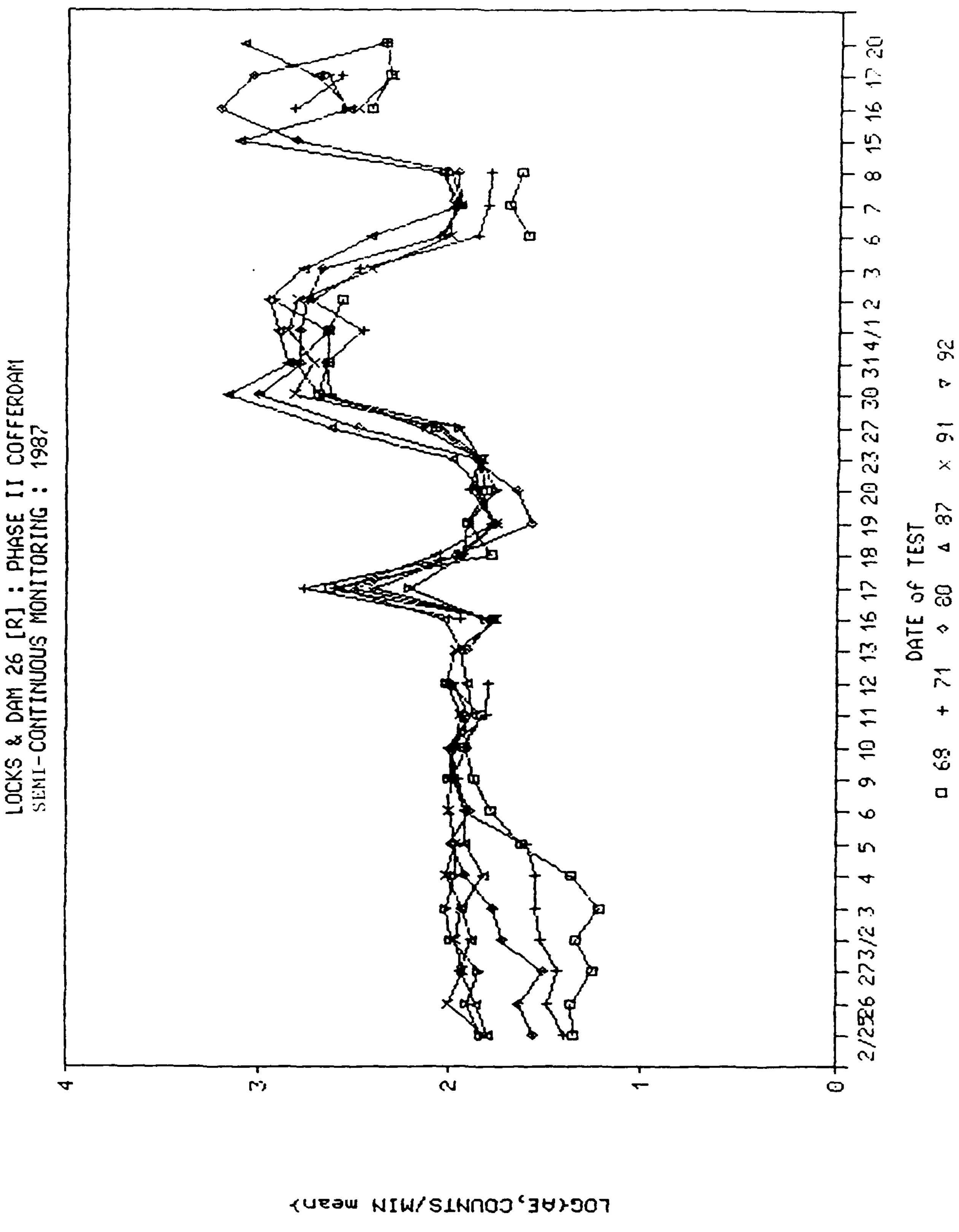


FIG 7.28 SEMI-CONTINUOUS MONITORING - SEMI-LOG SCALE

(CELLS 68, 71, 80, 87, 91, & 92)- FEBRUARY-APRIL 1987

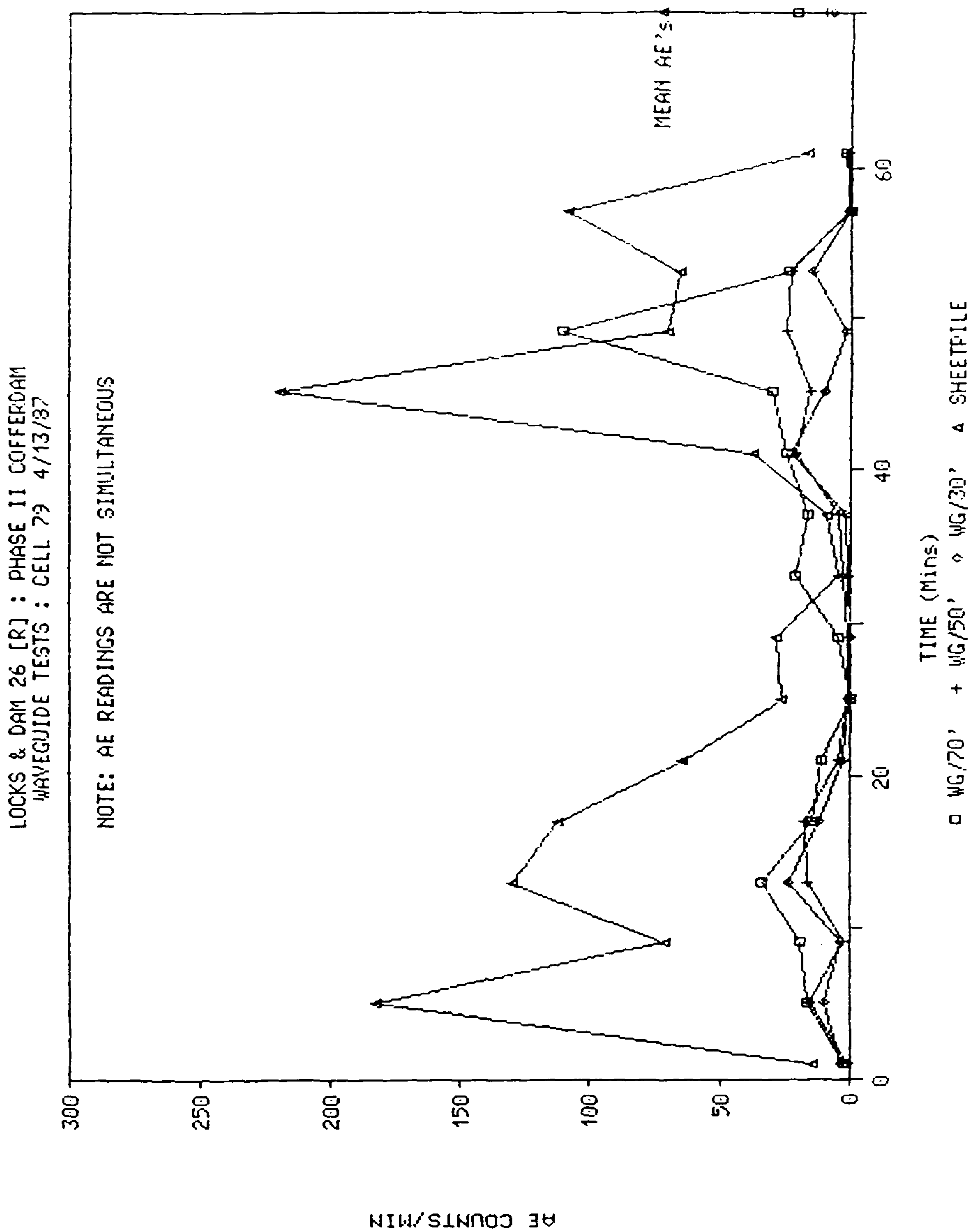


FIG 7.29 ATLAS MONITORING: CELL 79; APRIL 13, 1987

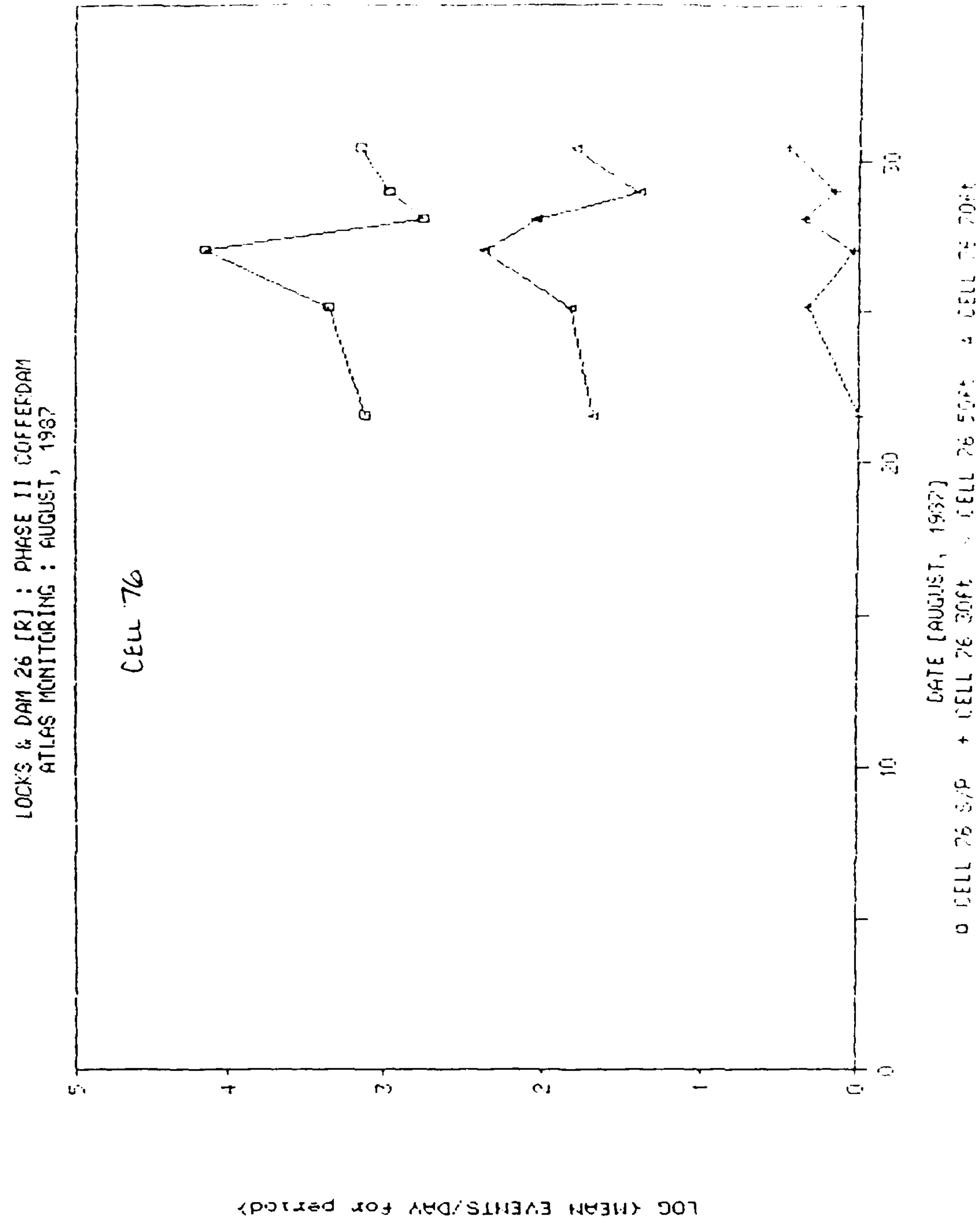


FIG 7.30 ATLAS MONITORING: CELL 76; AUGUST 1987

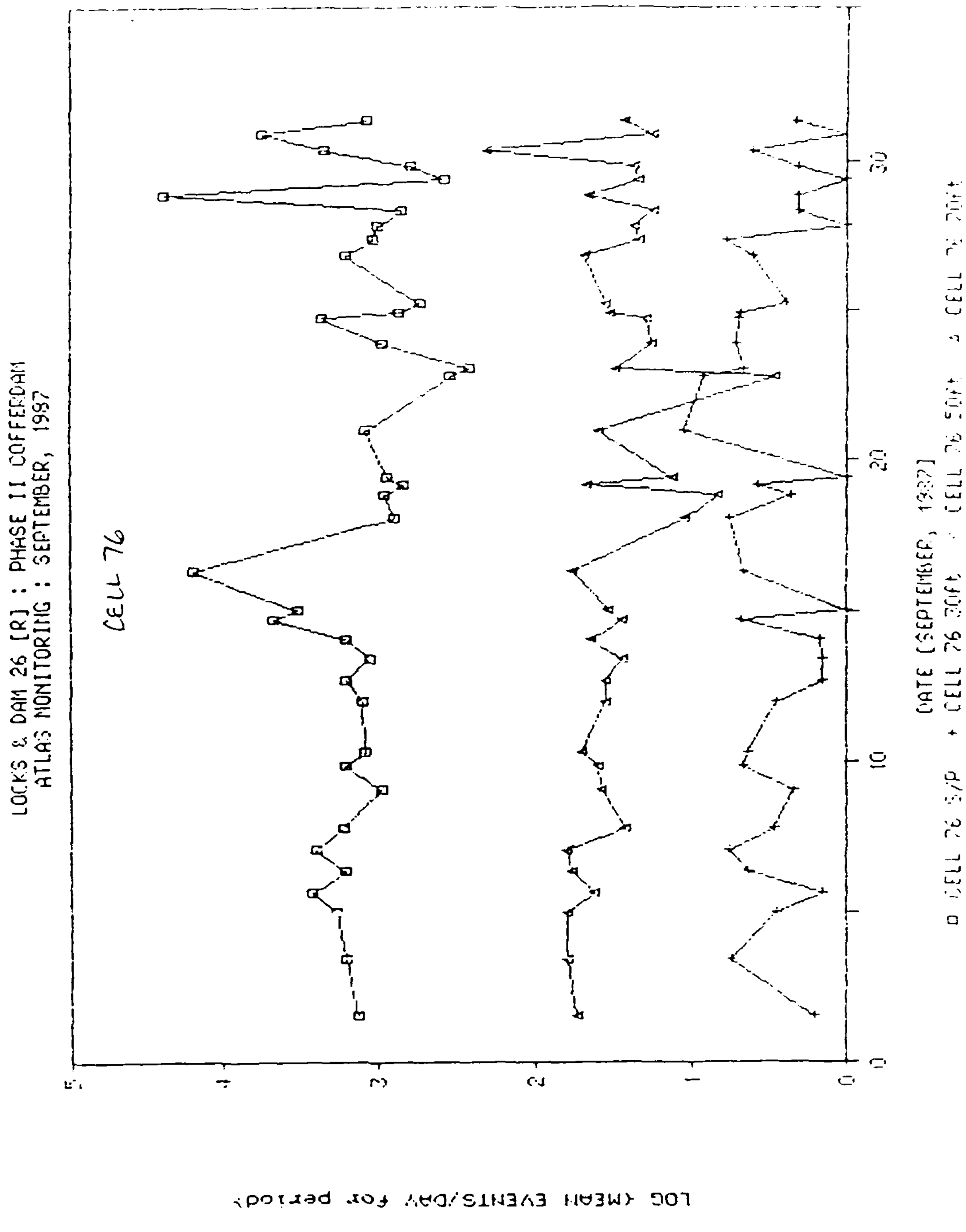


FIG 7.31 ATLAS MONITORING: CELL 76; SEPTEMBER 1987

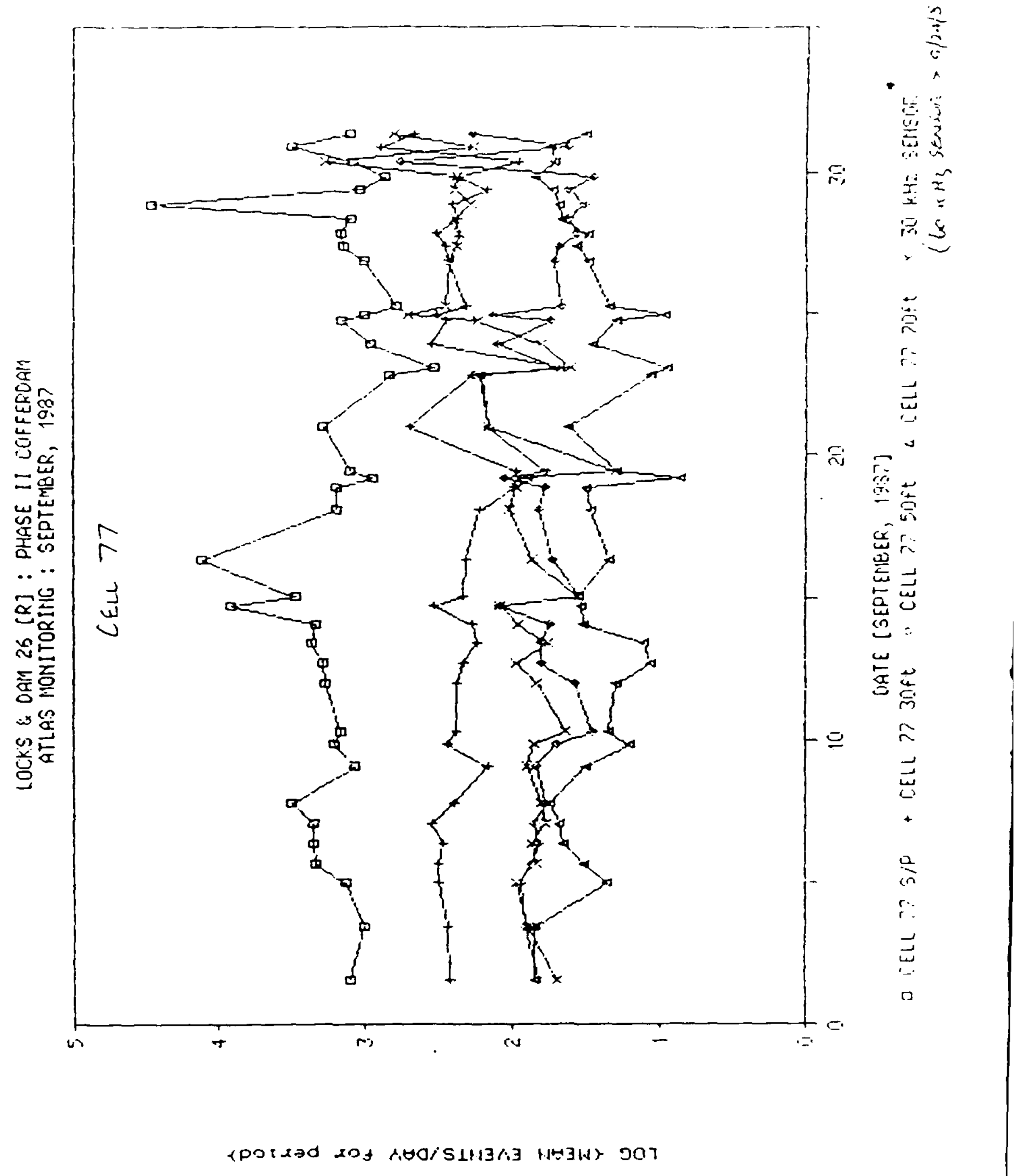


FIG 7.32 ATLAS MONITORING: CELL 77; SEPTEMBER 1987

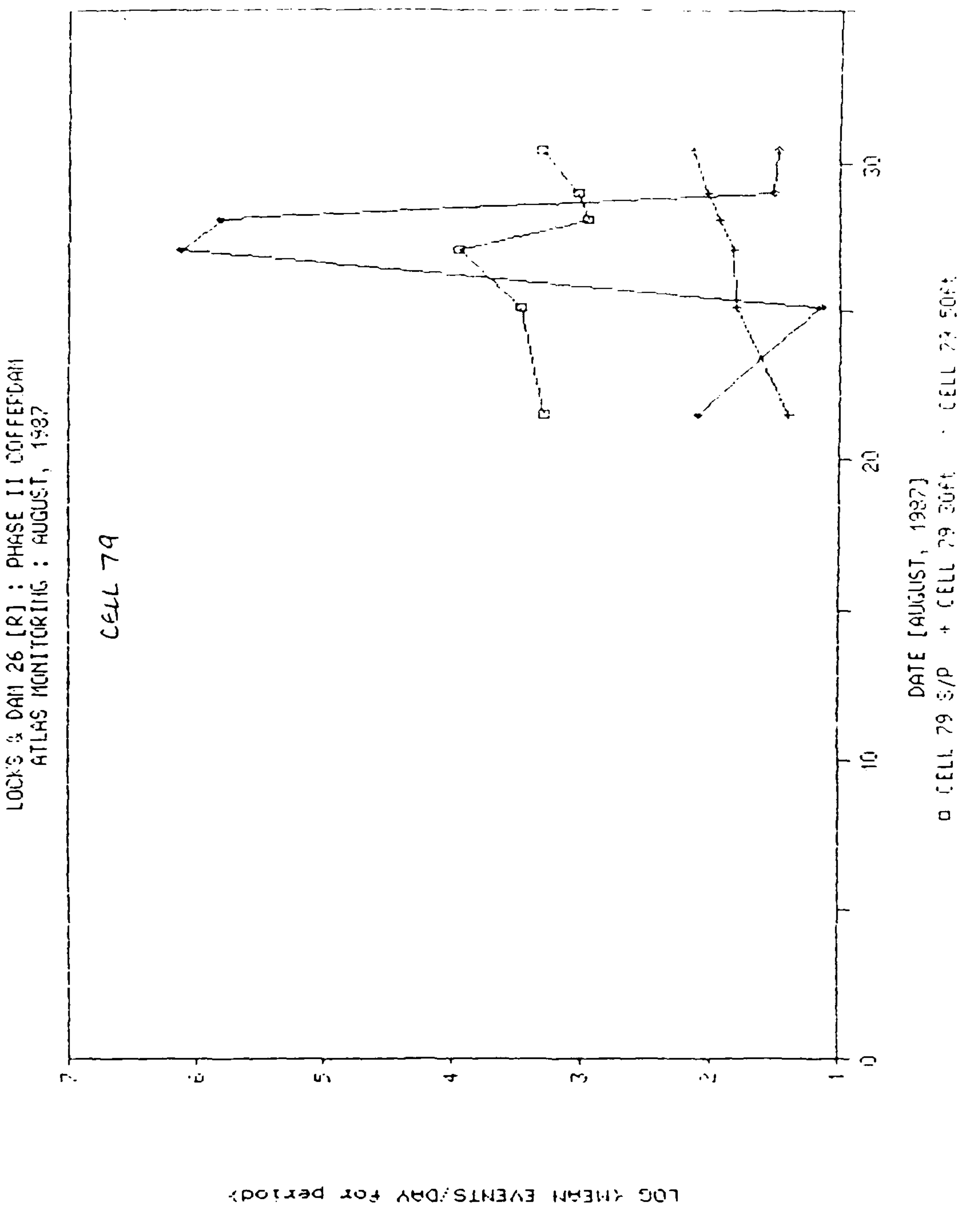


FIG 7.33 ATLAS MONITORING: CELL 79; AUGUST 1987

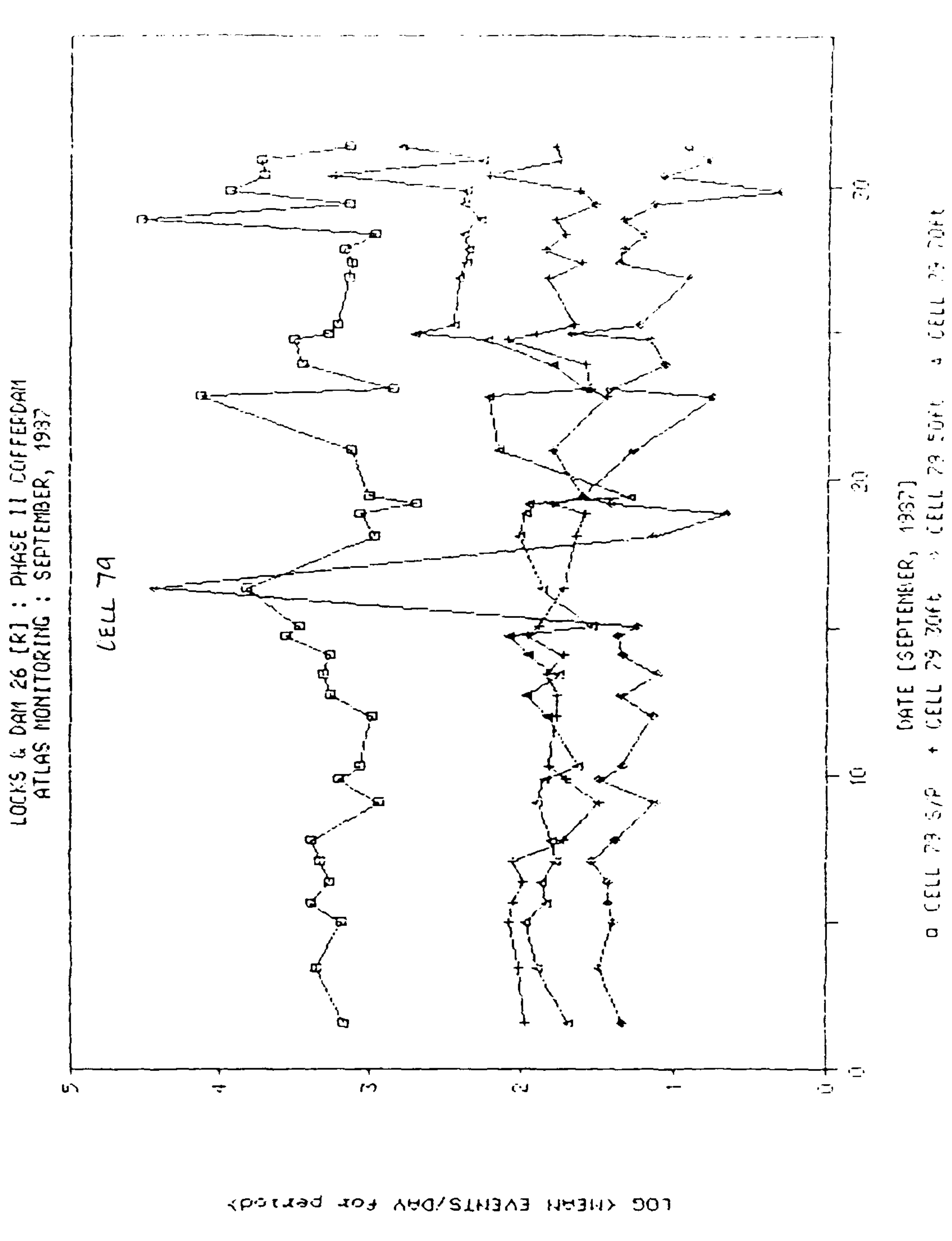


FIG 7.34 ATLAS MONITORING: CELL 79; SEPTEMBER 1987

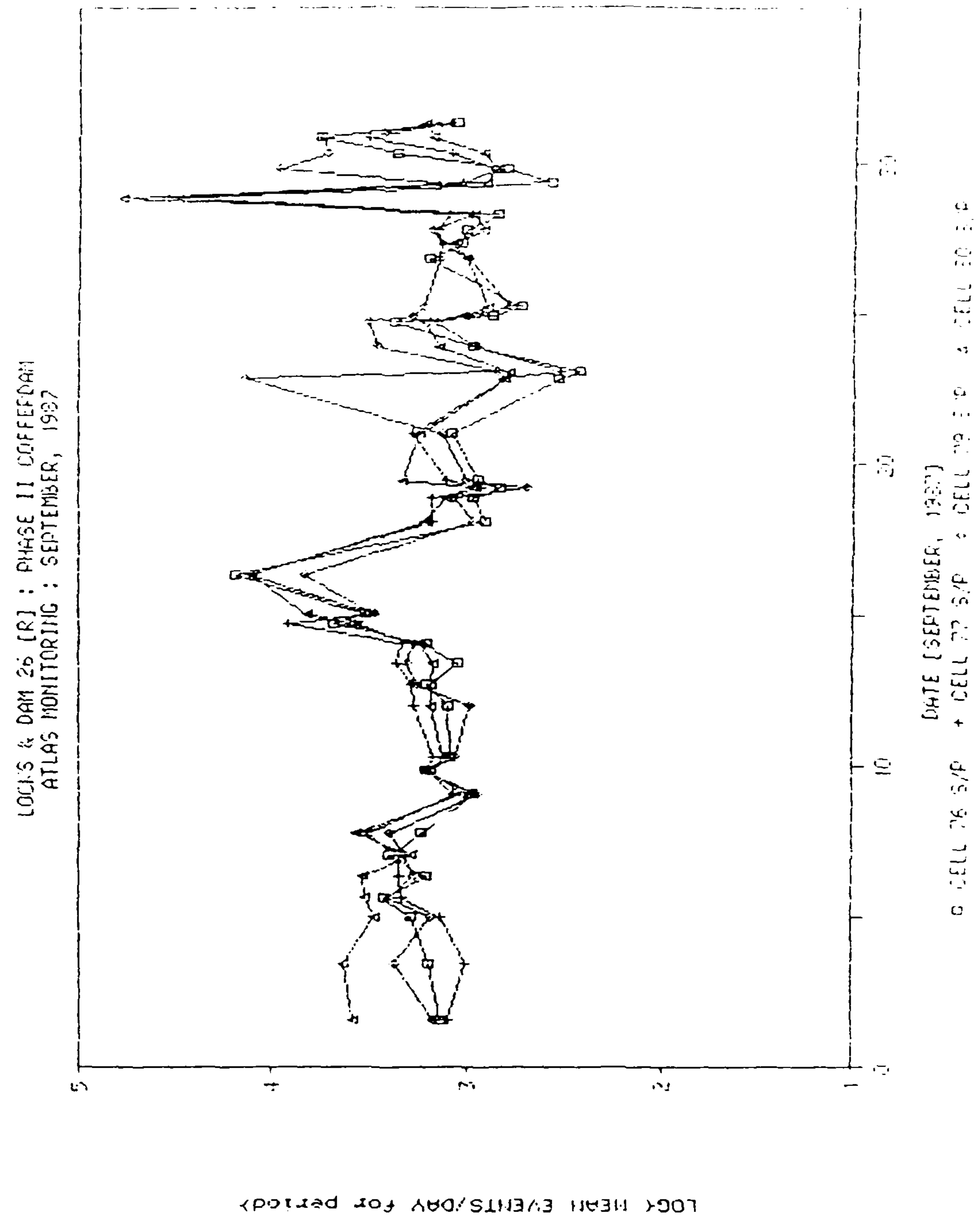


FIG 7.35 ATLAS MONITORING
SHEETPILE STATIONS:CELLS 76, 77, 79, 80

SEPTEMBER 1987

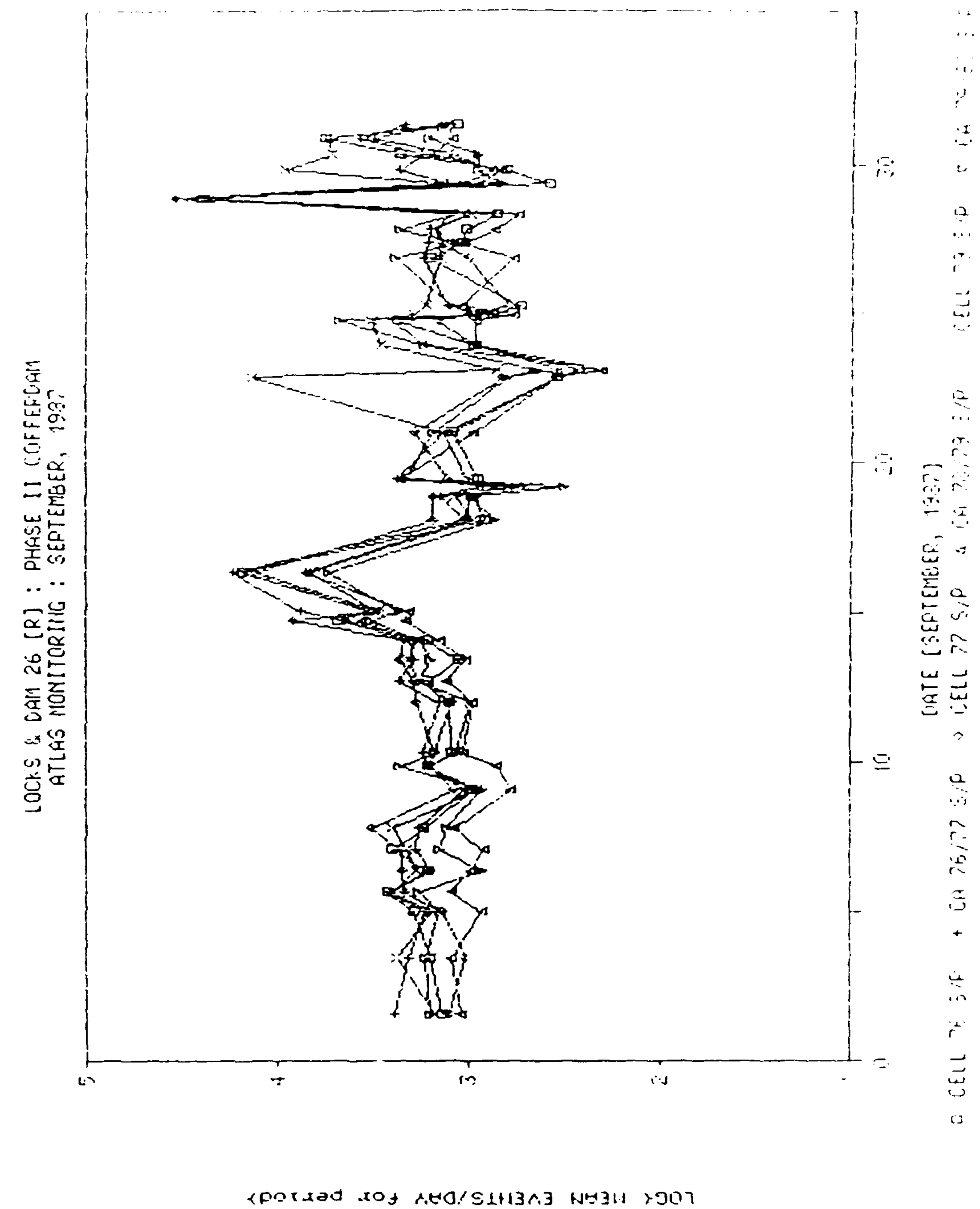


FIG 7.36 ATLAS MONITORING

SHEETPILE STATIONS:CELLS 76, 76/77, 77, 78/79, 79, 79/80

SEPTEMBER 1987

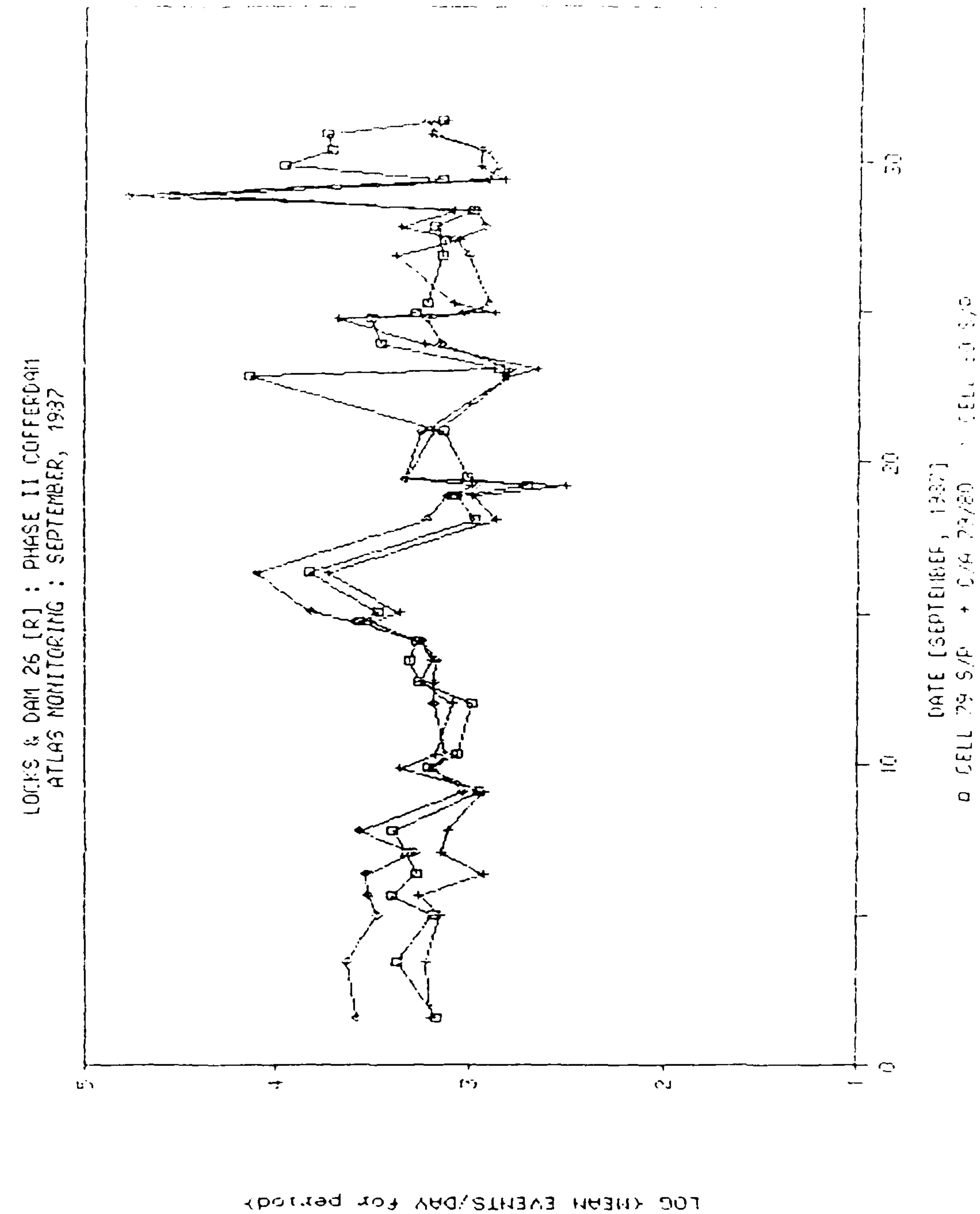


FIG 7.37 ATLAS MONITORING

SHEETPILE STATIONS: CELLS 79, 79/80, 80

SEPTEMBER 1987

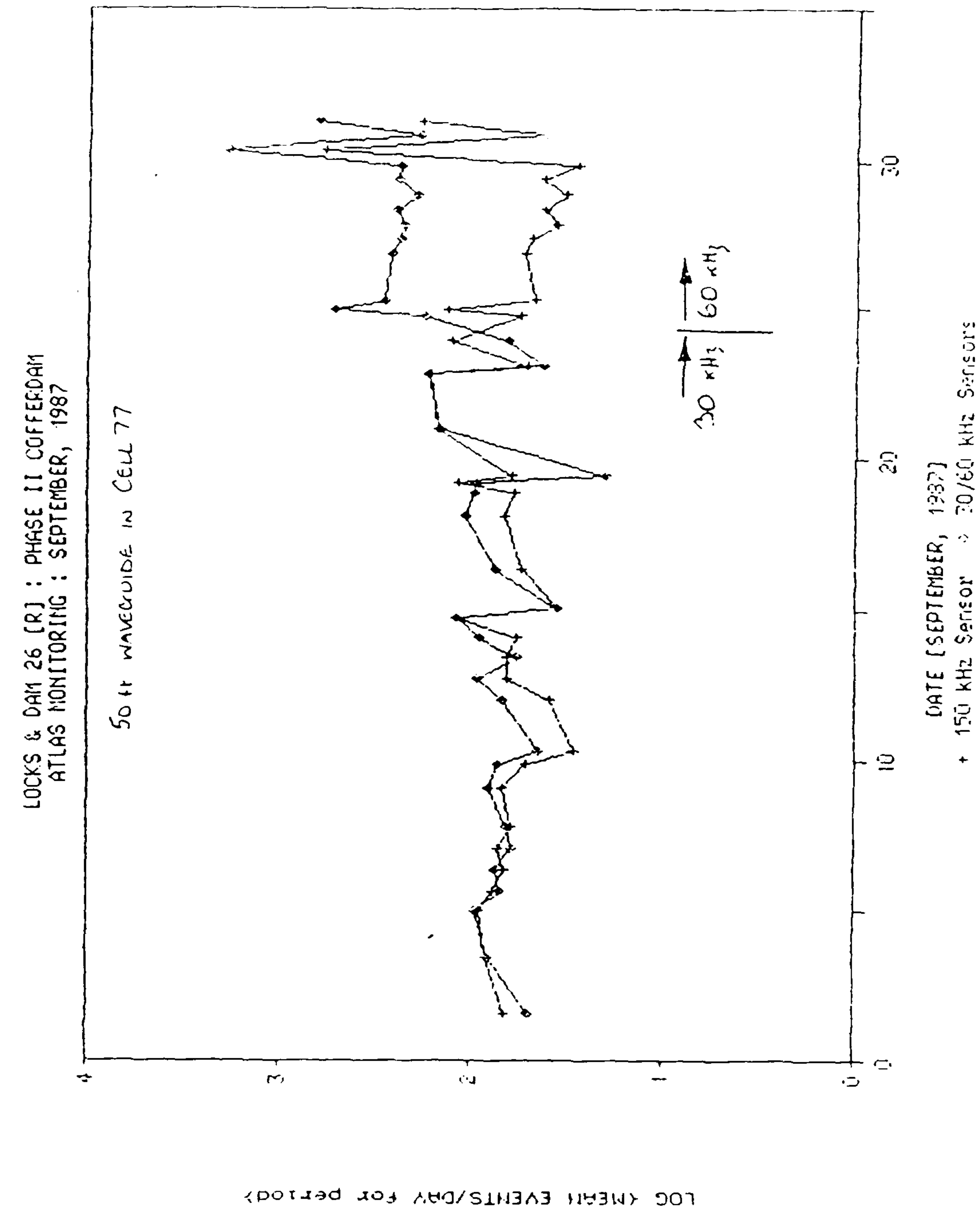


FIG 7.38 ATLAS MONITORING

WG-77.50.C

COMPARISON OF 30, 60, 150 KHZ SENSORS

SEPTEMBER 1987

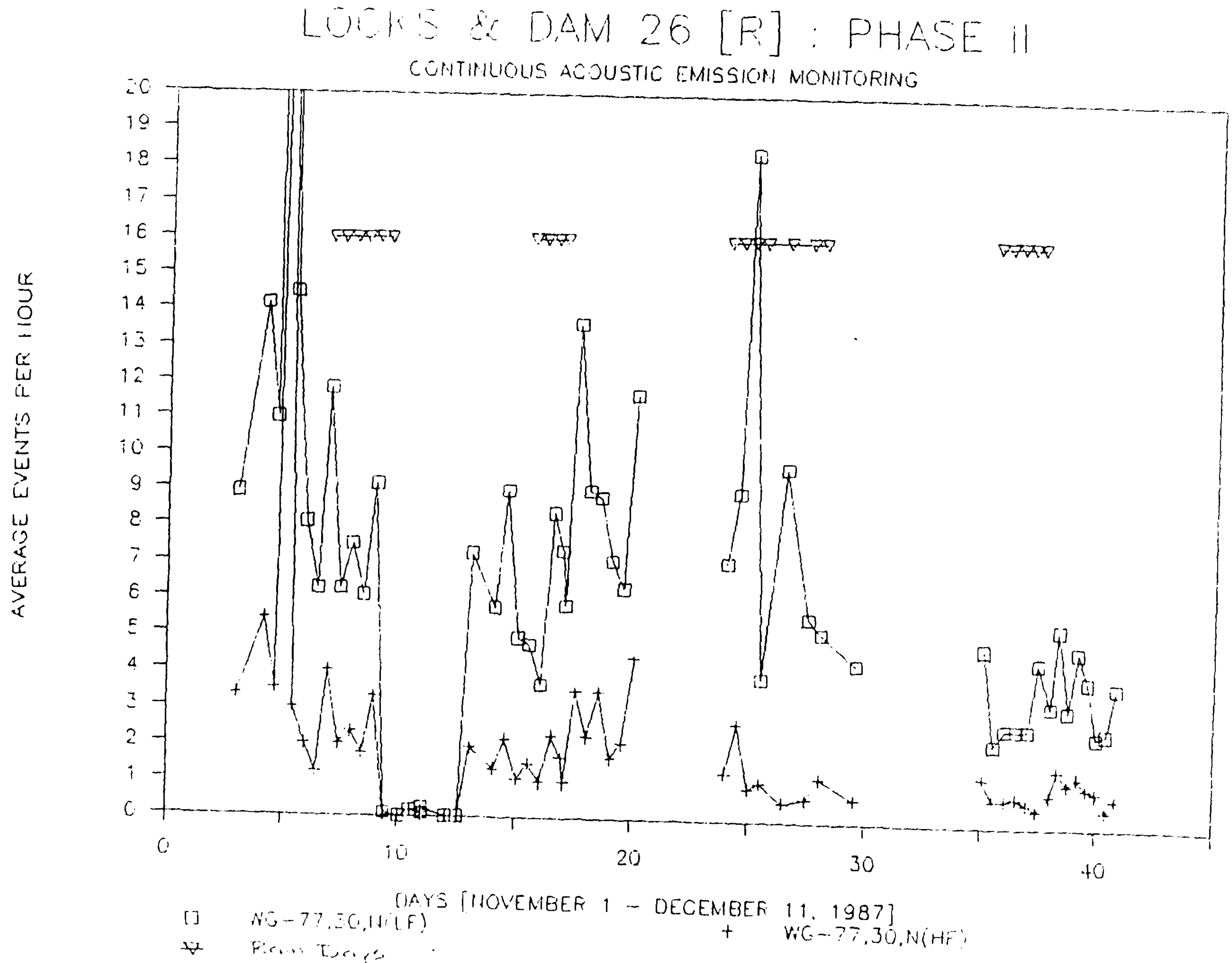


FIG 7.39 ATLAS MONITORING AVERAGE EVENTS PER HOUR
WG-77,30,N (LF), WG-77,30,N (HF) NOVEMBER-DECEMBER 1987

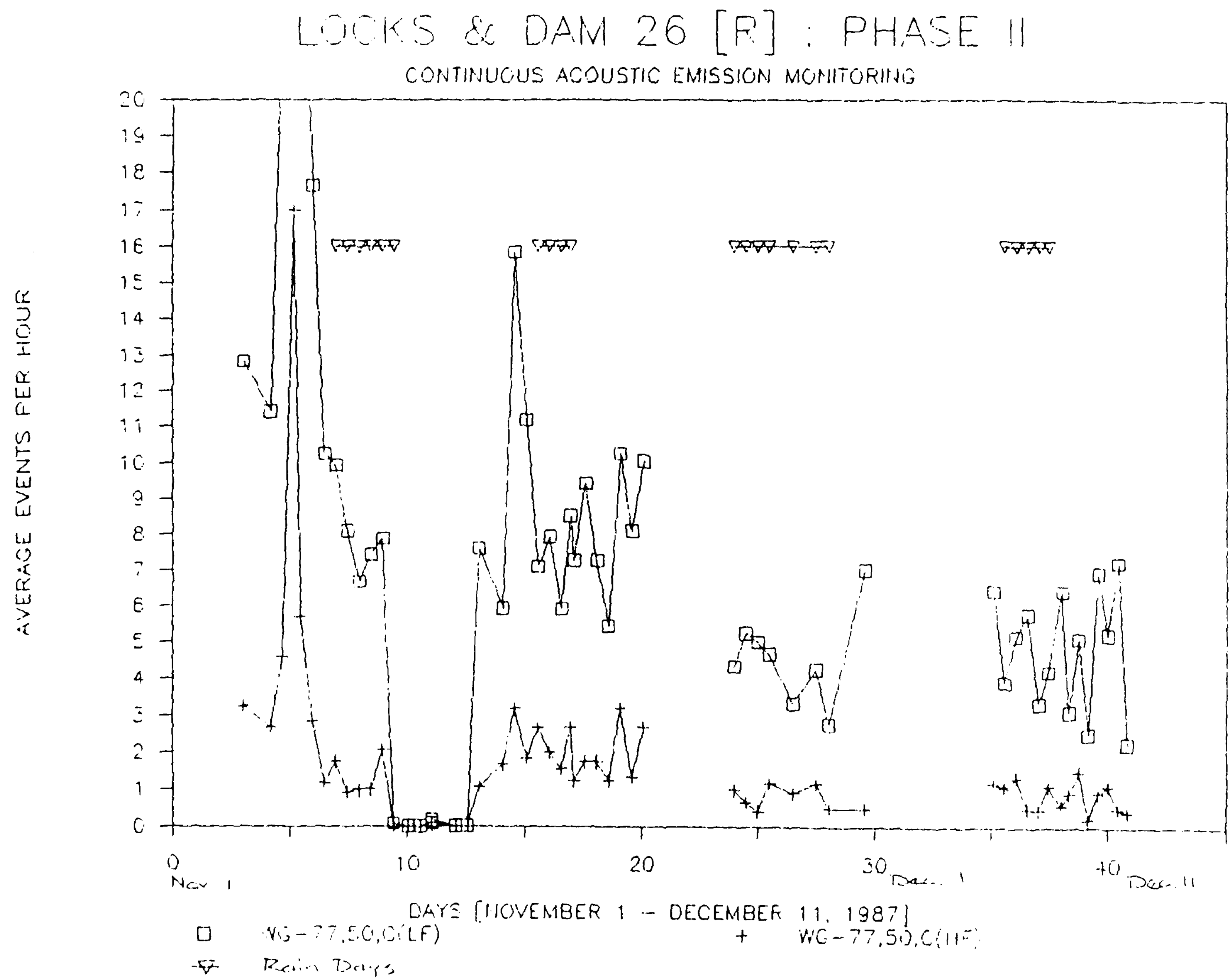


FIG 7.40 ATLAS MONITORING AVERAGE EVENTS PER HOUR

WG-77.50.C (LF), WG-77.50.C (HF) NOVEMBER-DECEMBER 1987

LOCKS & DAM 26 [R] : PHASE II

CONTINUOUS ACOUSTIC EMISSION MONITORING

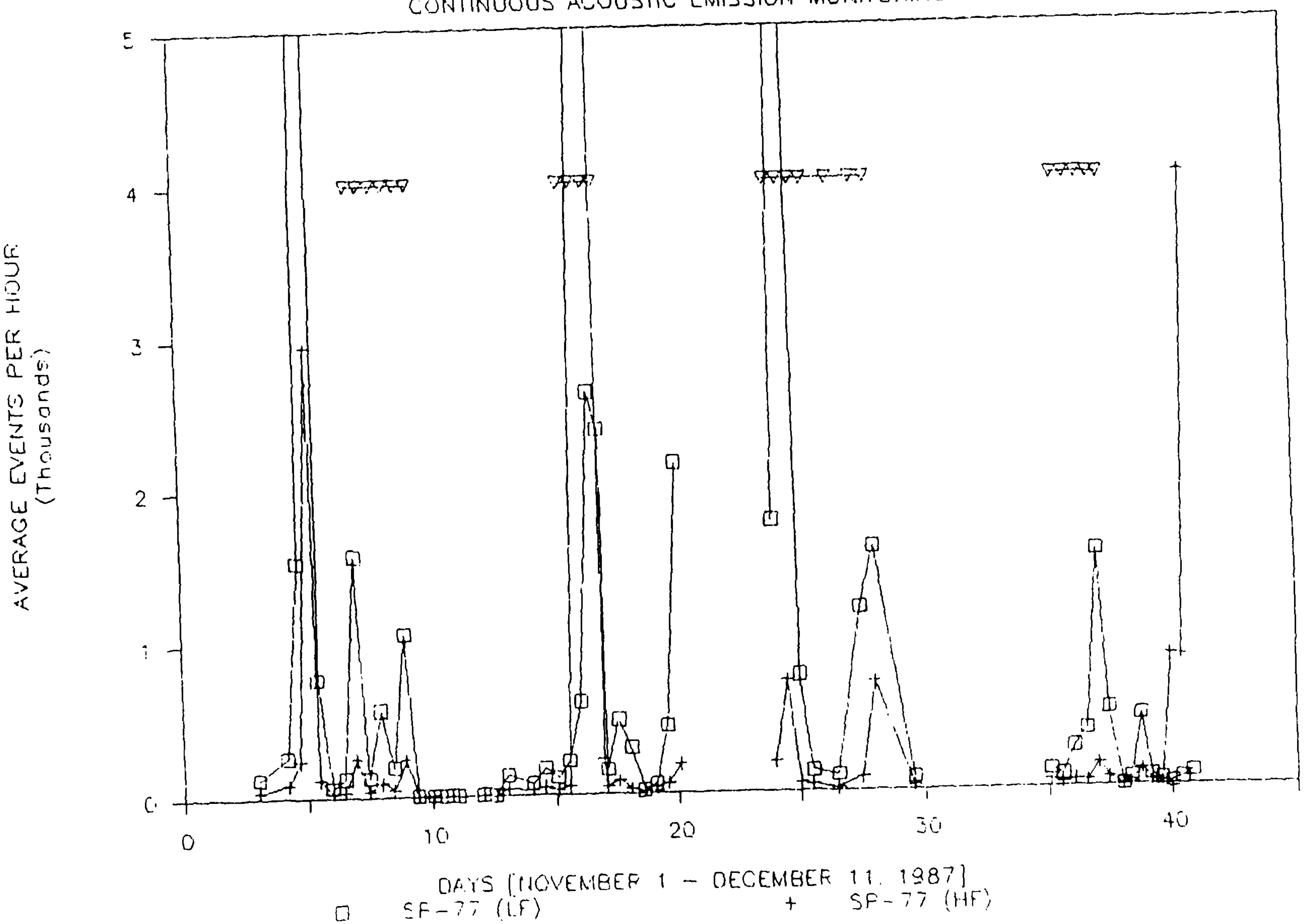


FIG 7.41 ATLAS MONITORING AVERAGE EVENTS PER HOUR
SP-77 (LF), SP-77 (HF) NOVEMBER-DECEMBER 1987

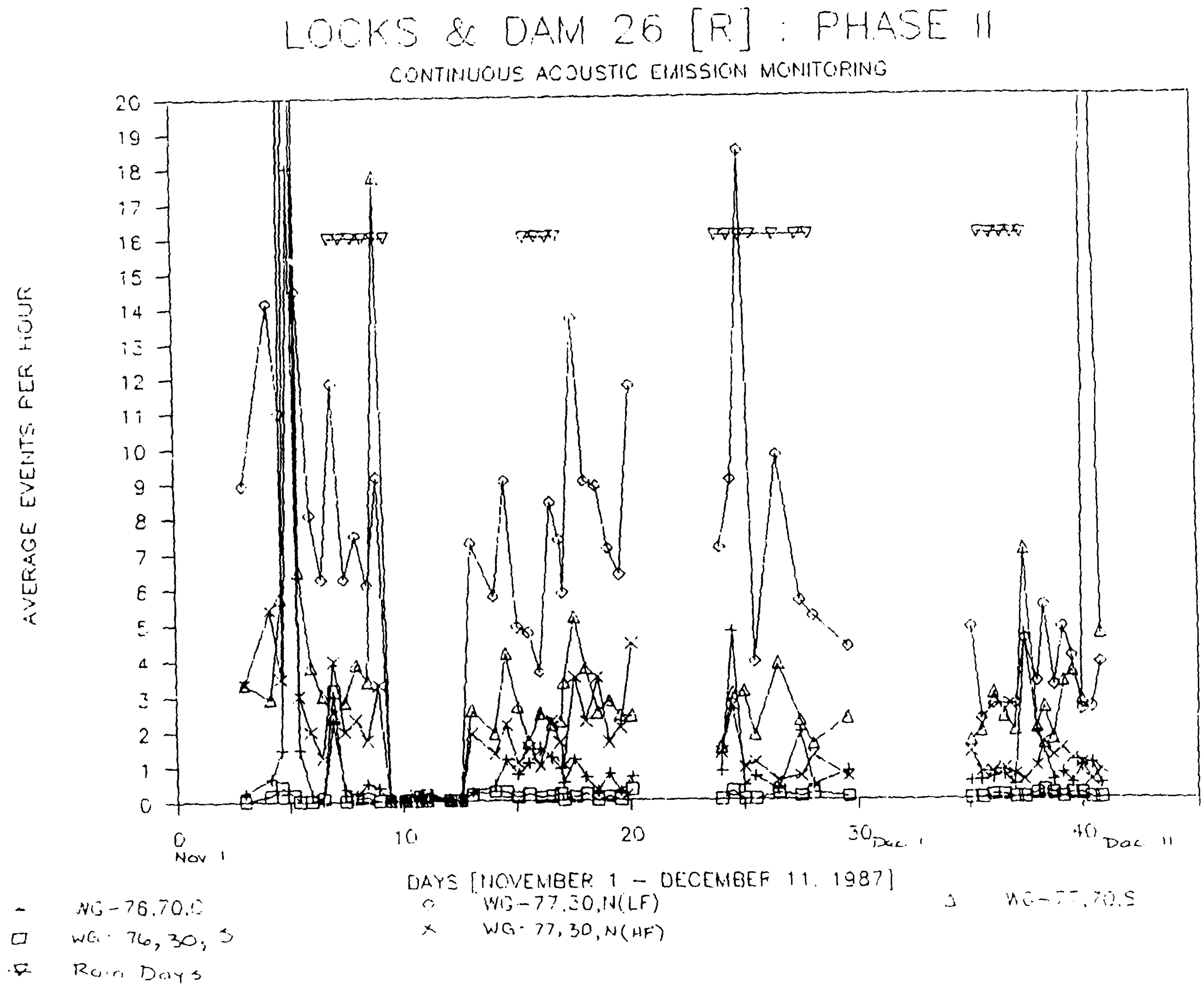


FIG. 7.52 ATLAS MONITORING AVERAGE EVENTS PER HOUR

WG-76.70.C, WG-77.30.N(LF), WG-77.70.S, WG-76.30.S, WG-77.30.N(HF) NOVEMBER-DECEMBER 1987

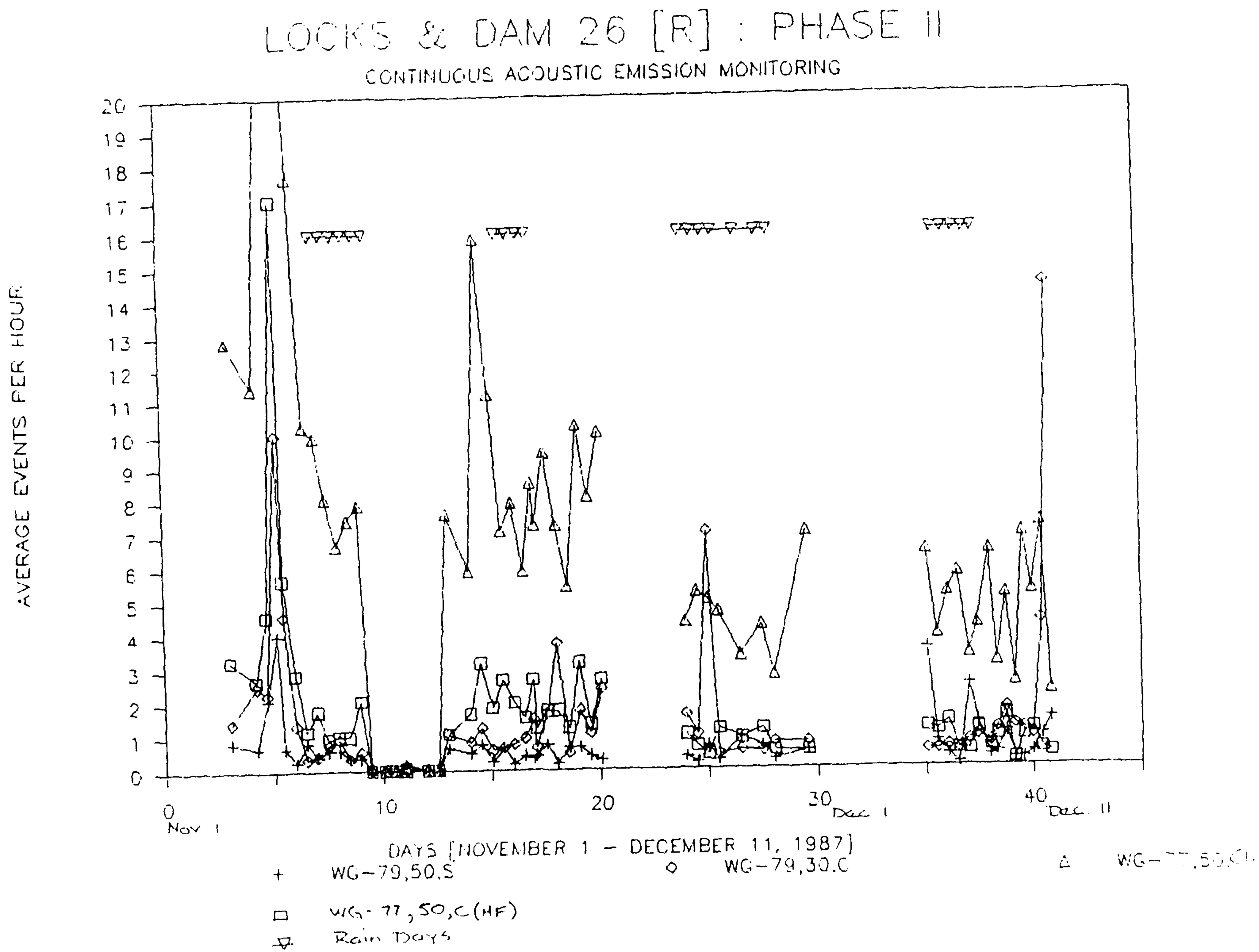


FIG 7.53 ATLAS MONITORING AVERAGE EVENTS PER HOUR

... NOVEMBER-DECEMBER 1987

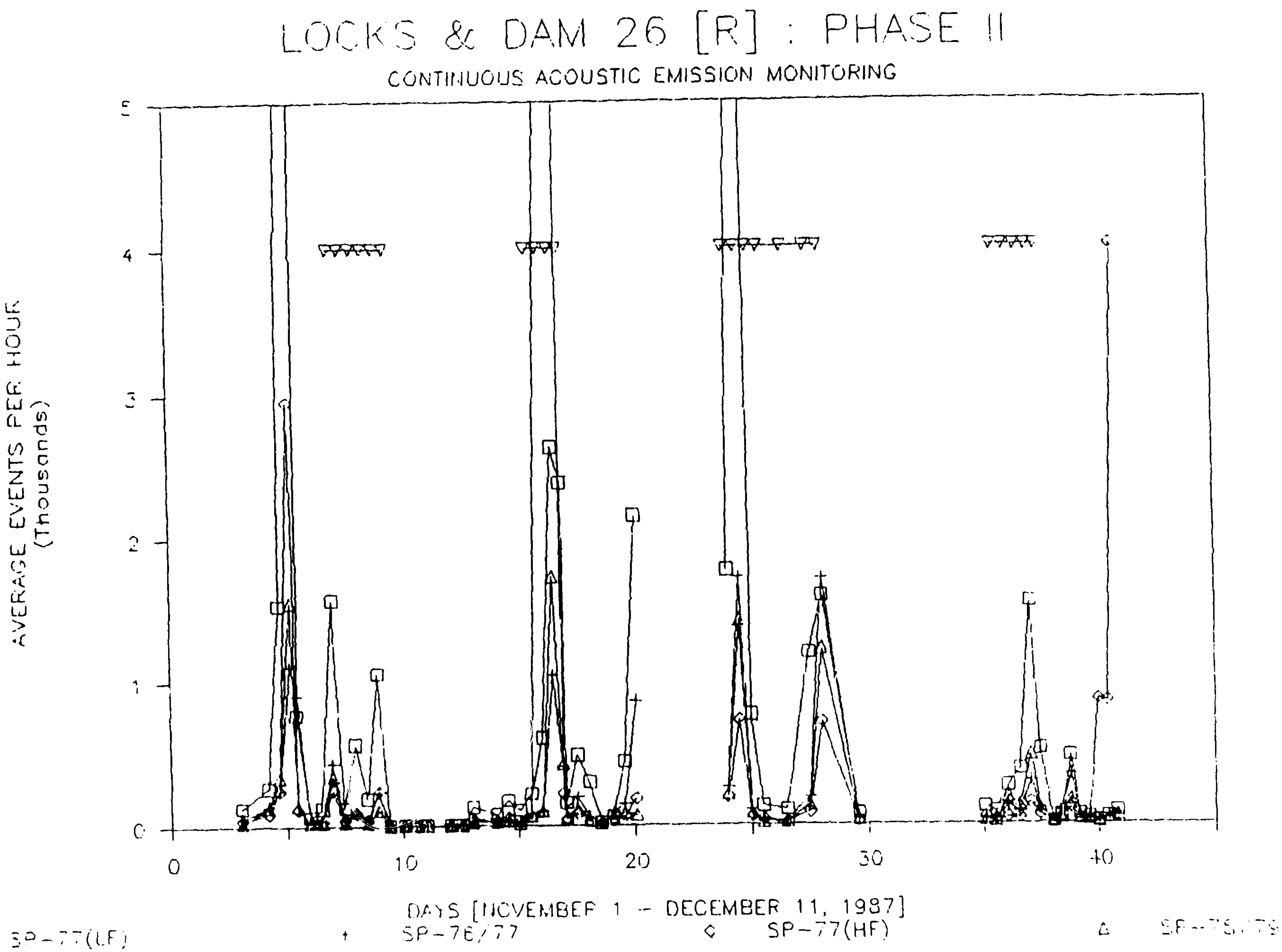


FIG 7.44 ATLAS MONITORING AVERAGE EVENTS PER HOUR

SP-77(LF), SP-76/77, SP-77(HF), SP-78/79 NOVEMBER-DECEMBER 1987

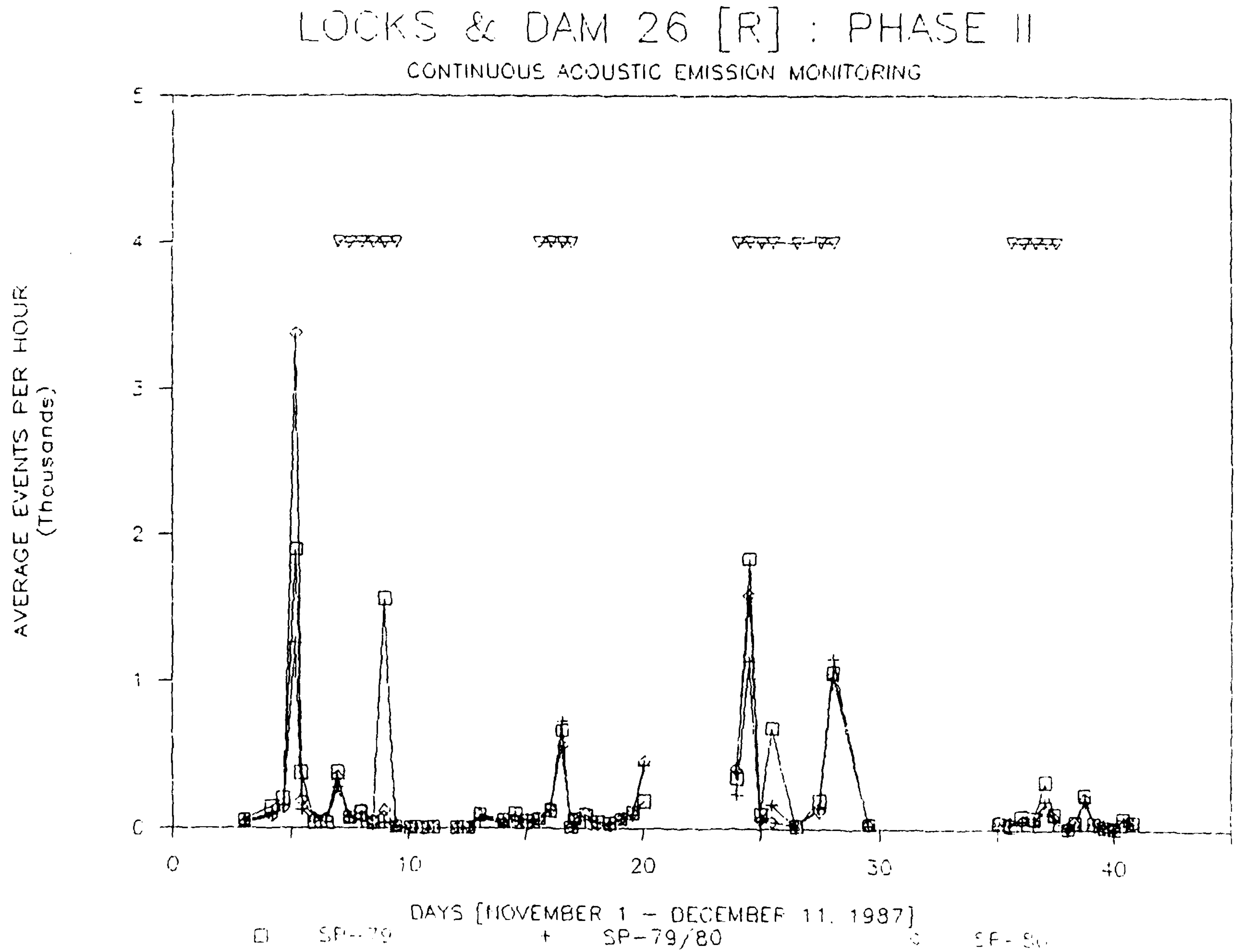


FIG 7.45 ATLAS MONITORING AVERAGE EVENTS PER HOUR SP-79, SP-79/80, SP-80 NOVEMBER-DECEMBER 1987

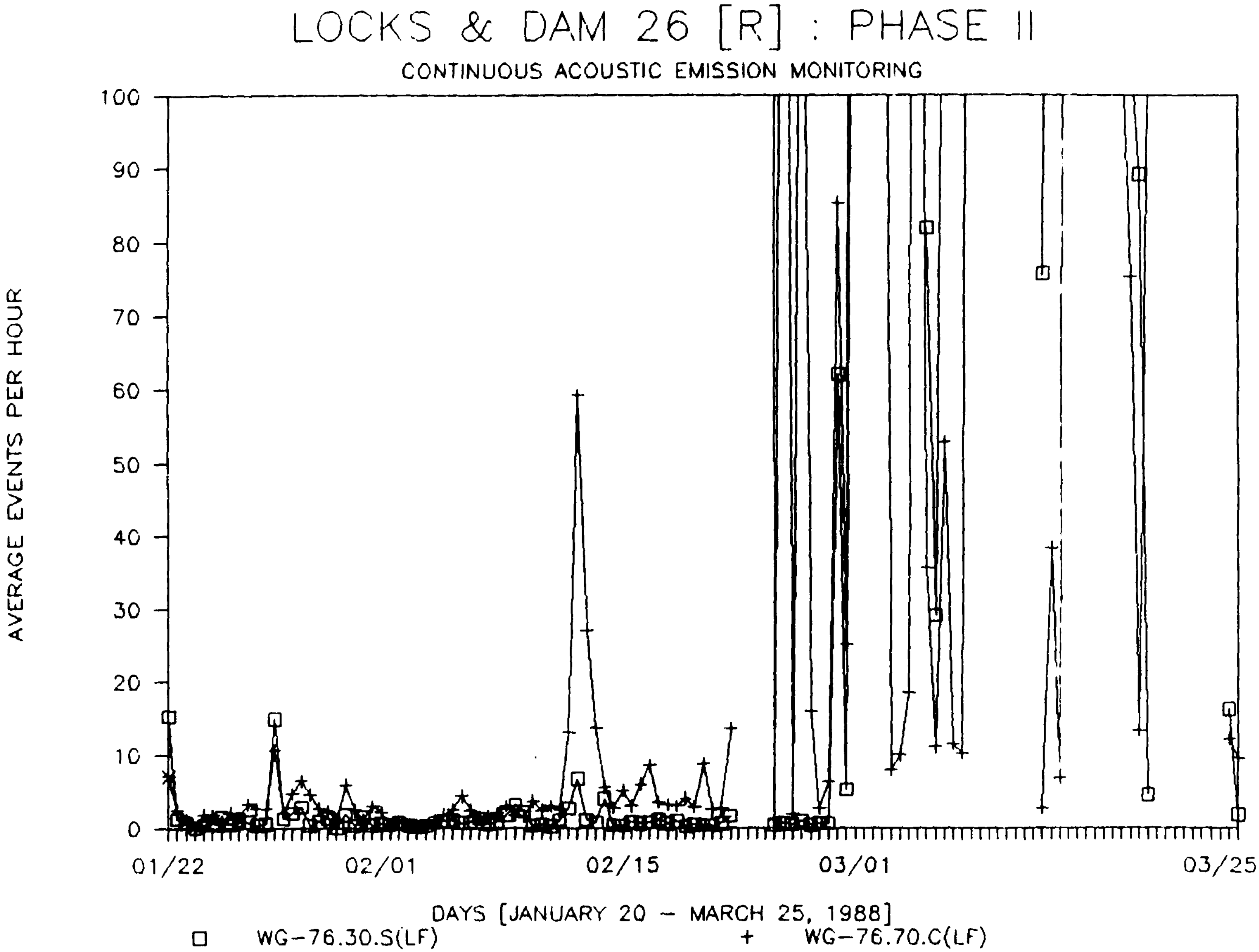


FIG 7.46 ATLAS MONITORING AVERAGE EVENTS PER HOUR
WG-76.30.S(LF), WG-76.70.C(LF) JANUARY-MARCH 1988

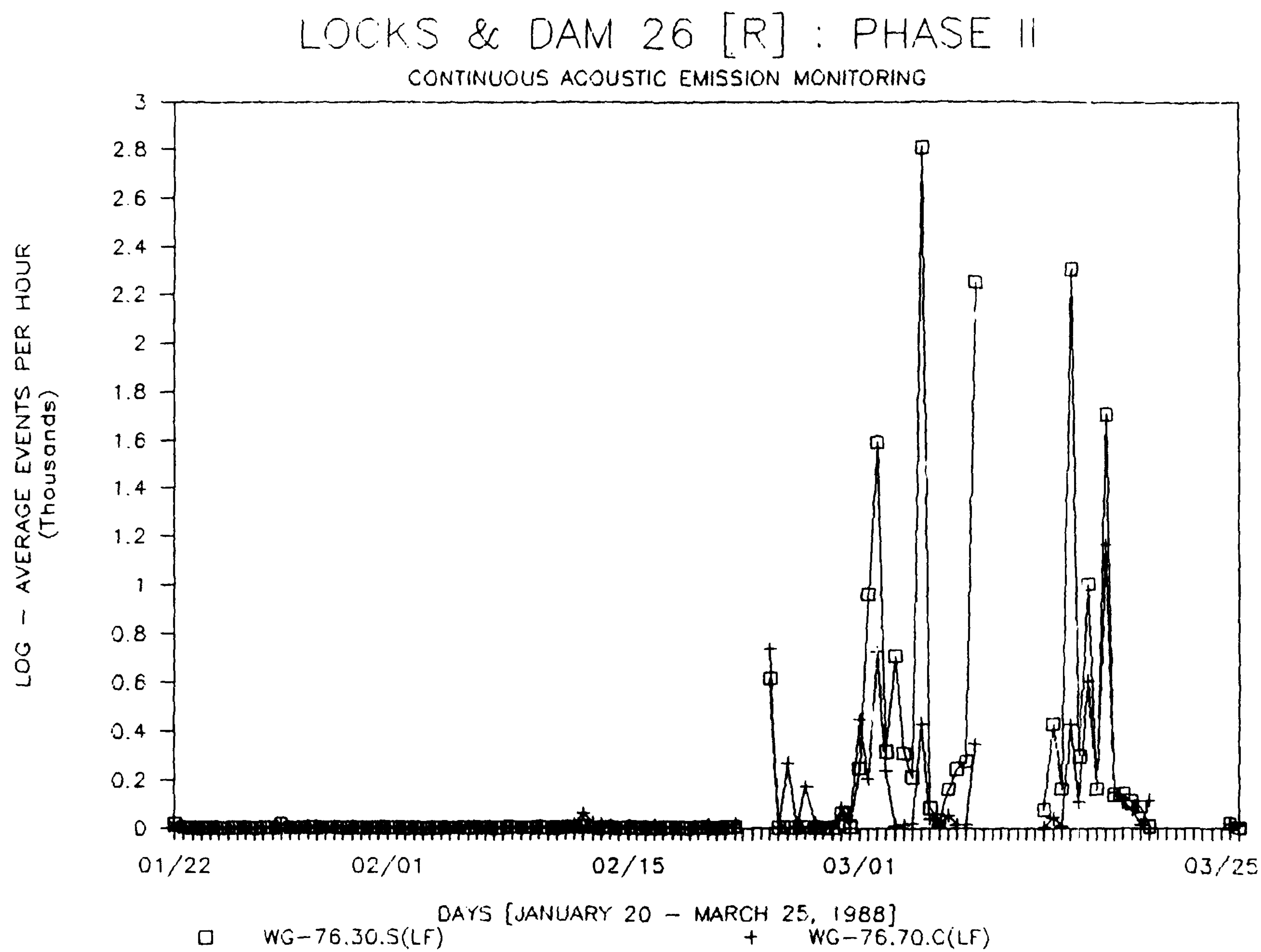


FIG 7.47 ATLAS MONITORING AVERAGE EVENTS PER HOUR

WG-76.30.S(LF), WG-76.70.C(LF) SEMI-LOG SCALE JANUARY-MARCH 1988

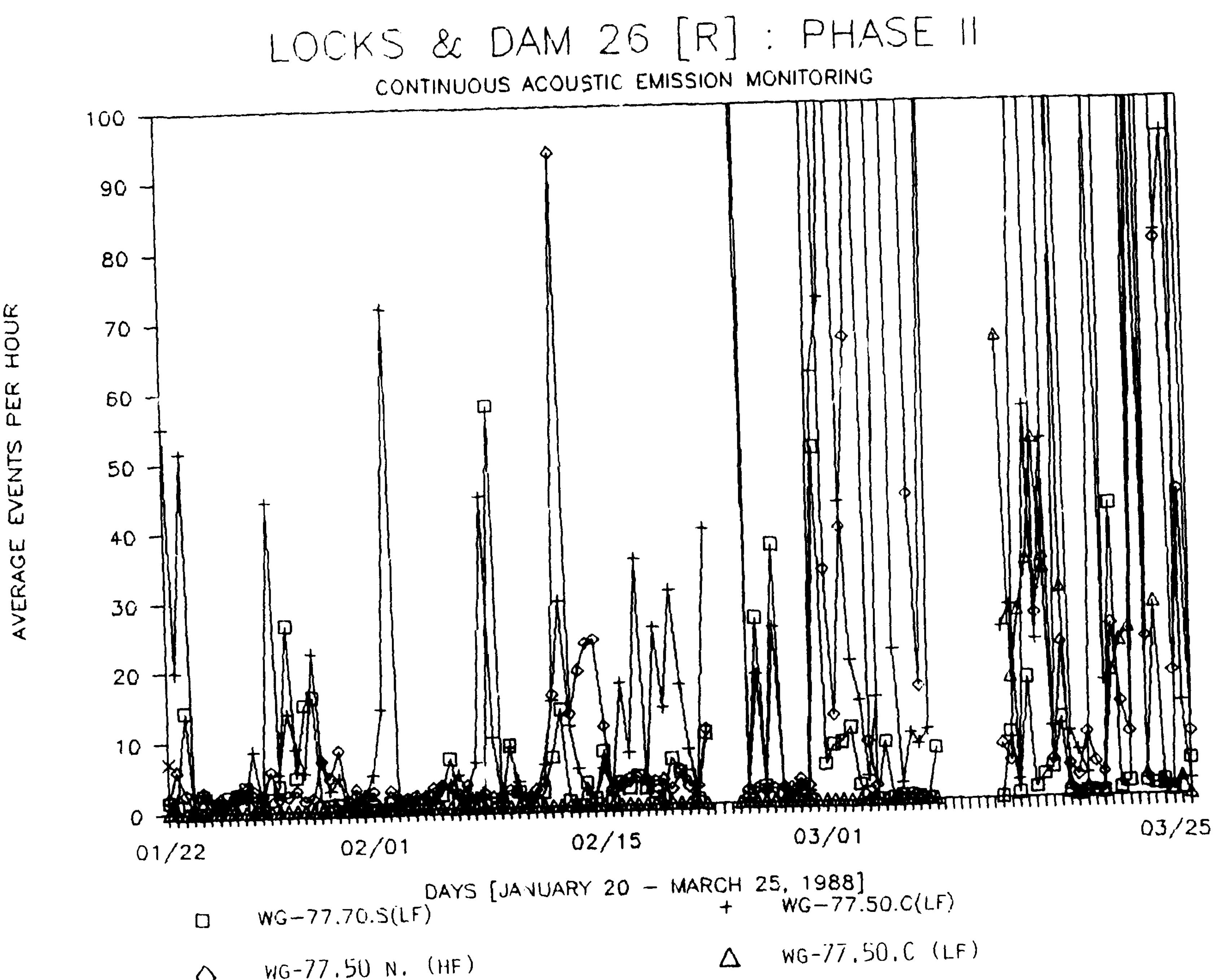


FIG 7.48 ATLAS MONITORING AVERAGE EVENTS PER HOUR
WG-77.70.S(LF), WG-77.50.C(LF), WG-77.50 N. (HF), WG-77.50.C (LF) JANUARY-MARCH 1988

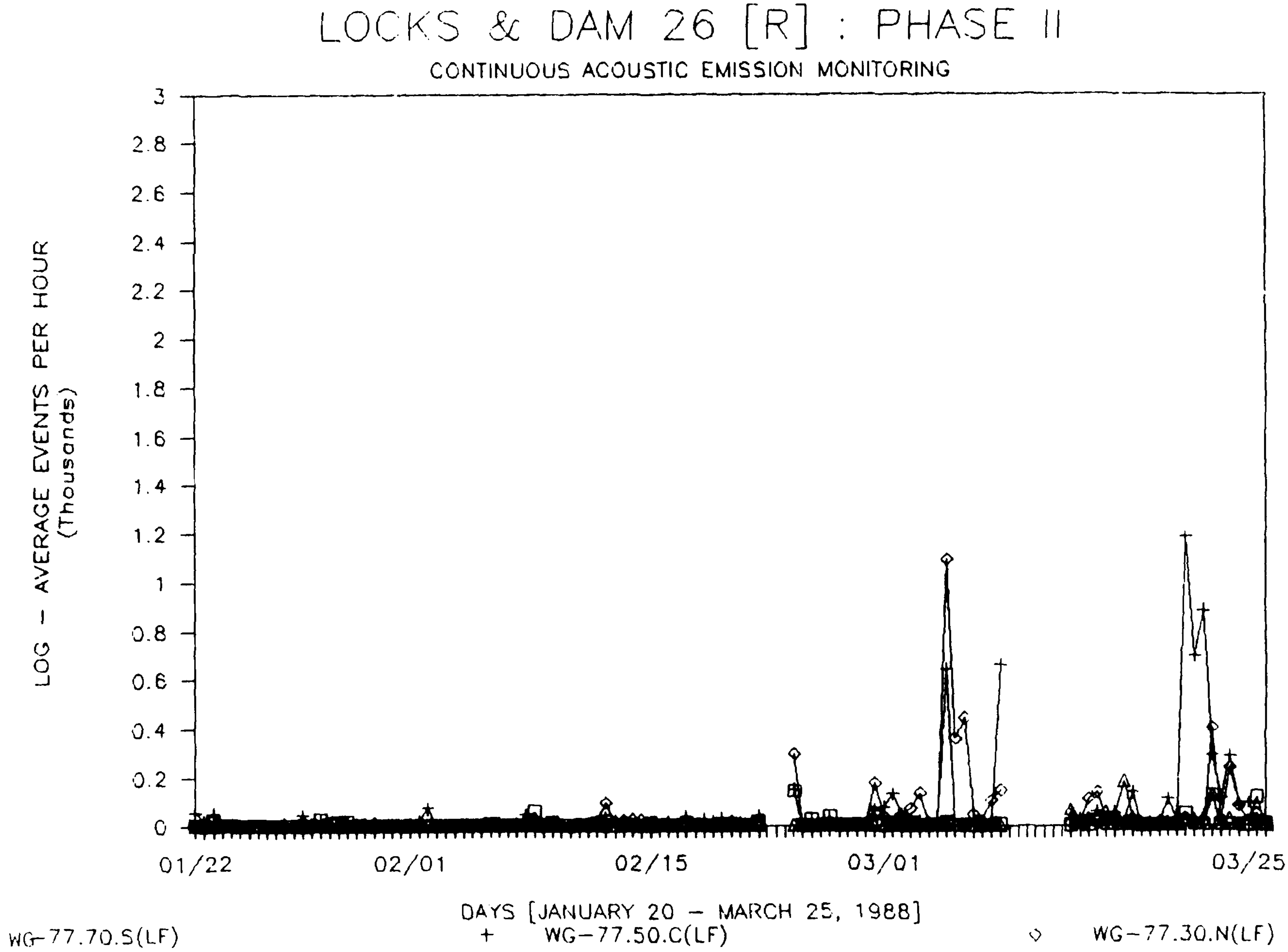


FIG 7.49 ATLAS MONITORING AVERAGE EVENTS PER HOUR

WG-77.70.S(LF), WG-77.50.C(LF), WG-77.30.N(LF) SEMI LOG SCALE JANUARY-MARCH 1988

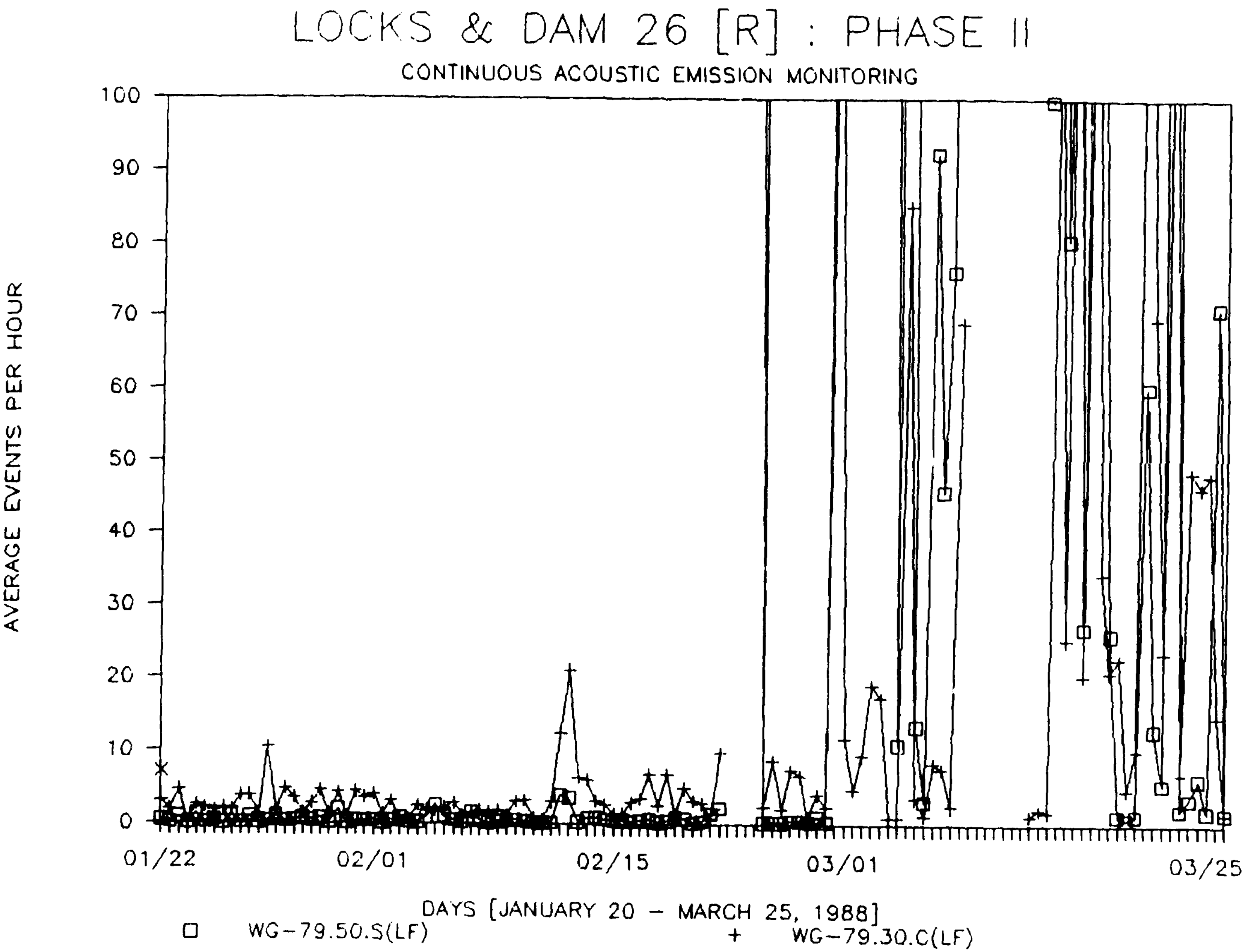


FIG 7.50 ATLAS MONITORING AVERAGE EVENTS PER HOUR

WG-79.50.S(LF), WG-79.30.C(LF) JANUARY-MARCH 1988

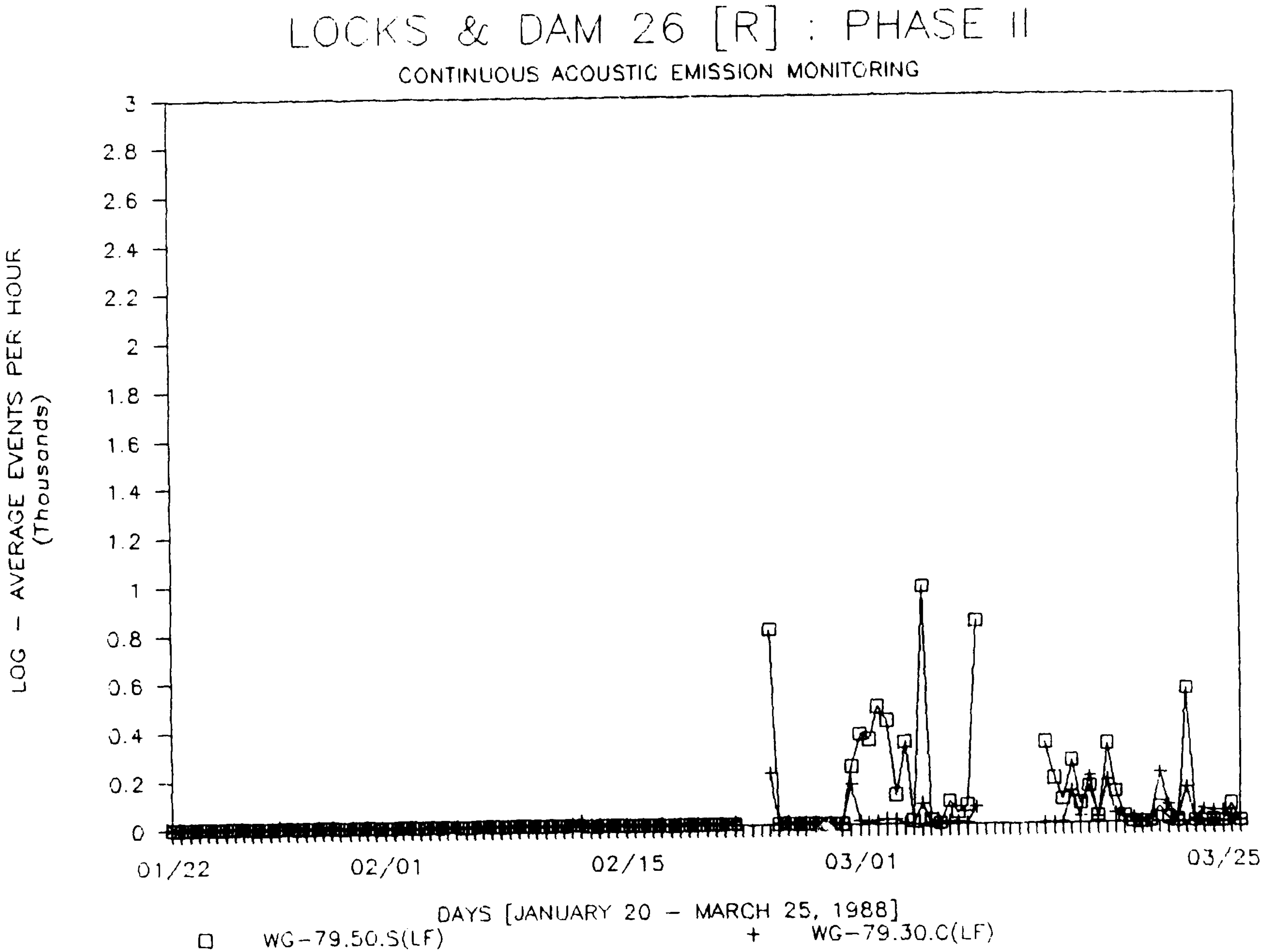


FIG 7.51 ATLAS MONITORING AVERAGE EVENTS PER HOUR

WG-79.50.S(LF), WG-79.30.C(LF) SEMI-LOG SCALE JANUARY-MARCH 1988

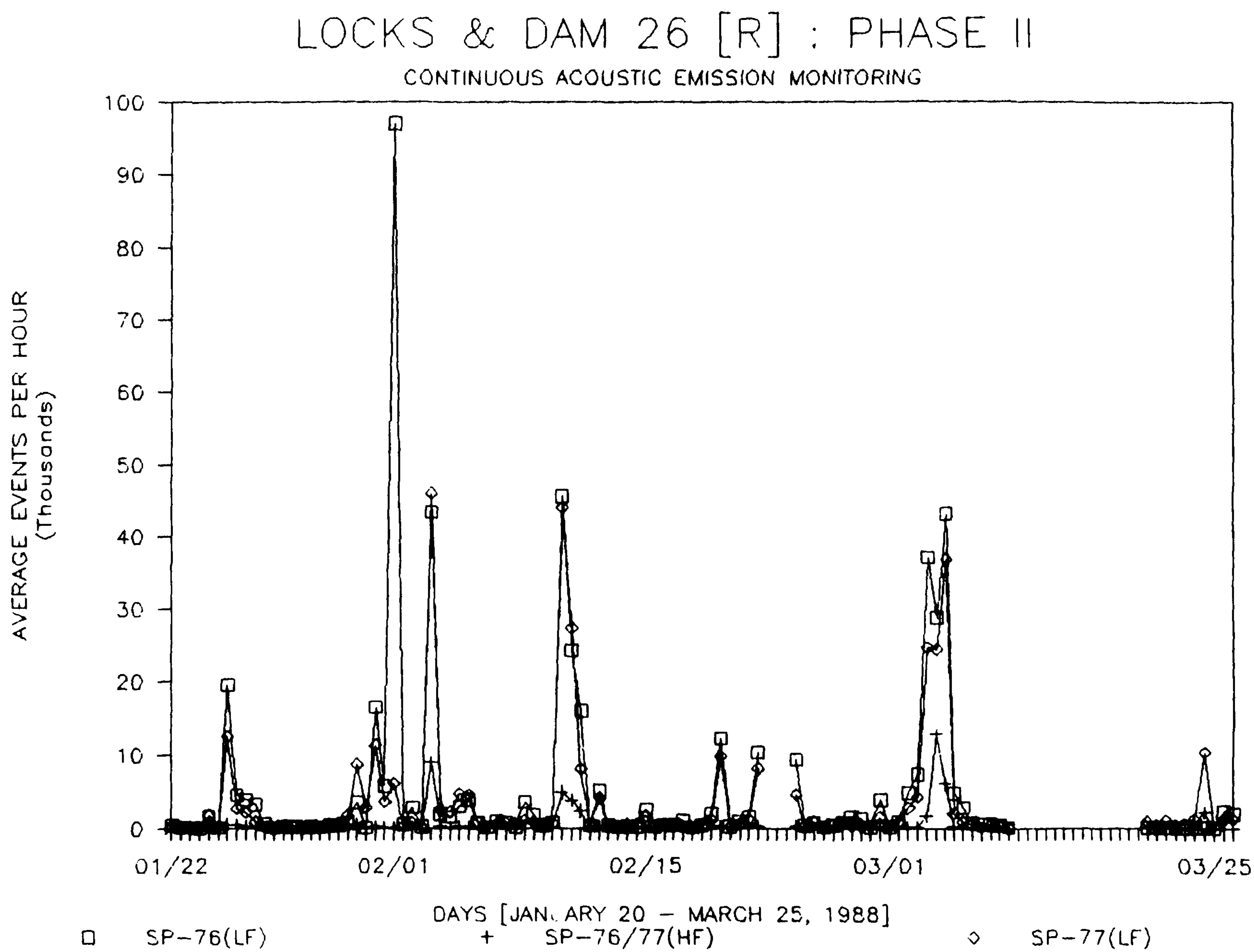


FIG 7.52 ATLAS MONITORING AVERAGE EVENTS PER HOUR

SP-76(LF), SP-76/77(HF), SP-77(LF) JANUARY-MARCH 1988

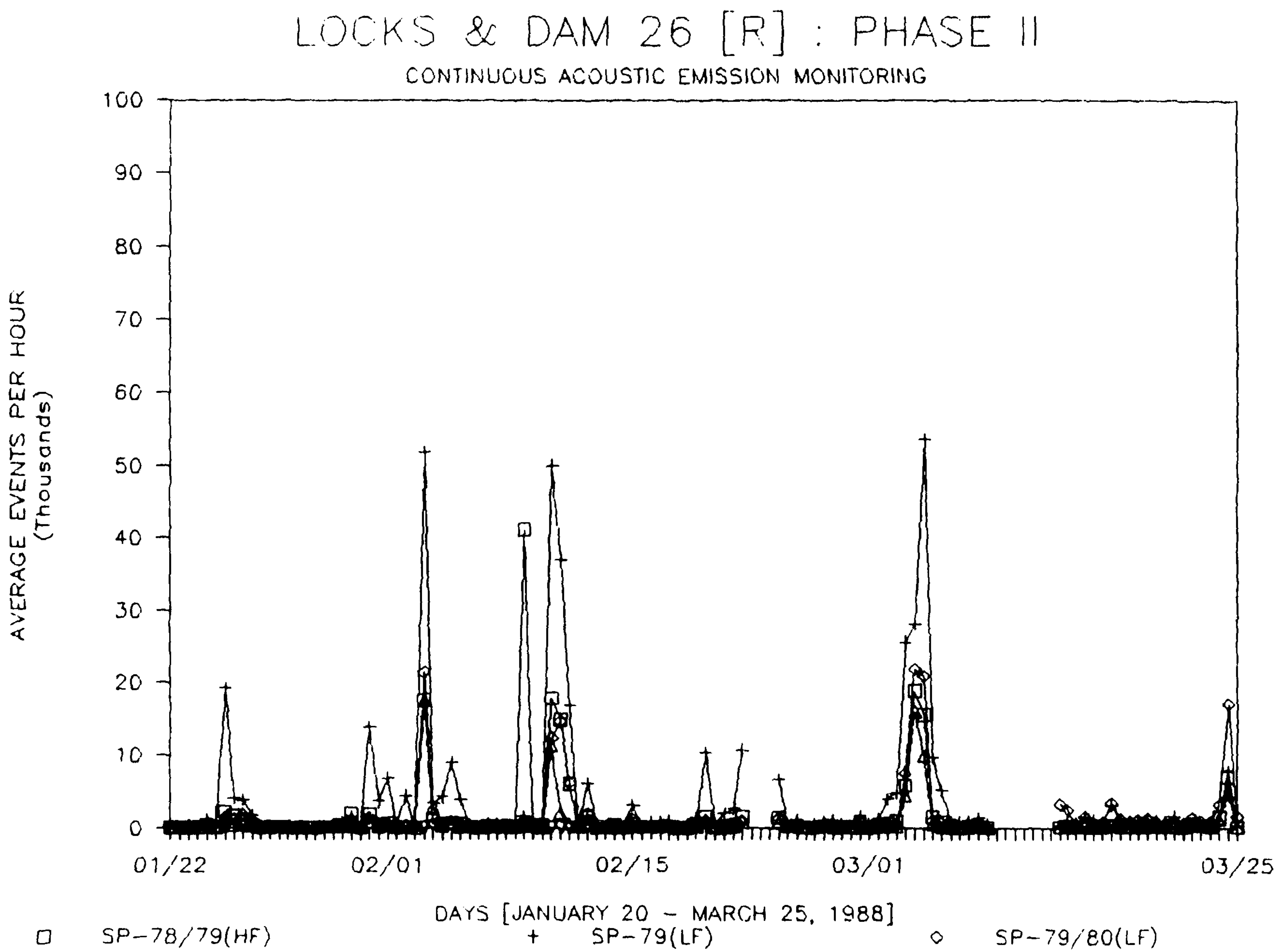
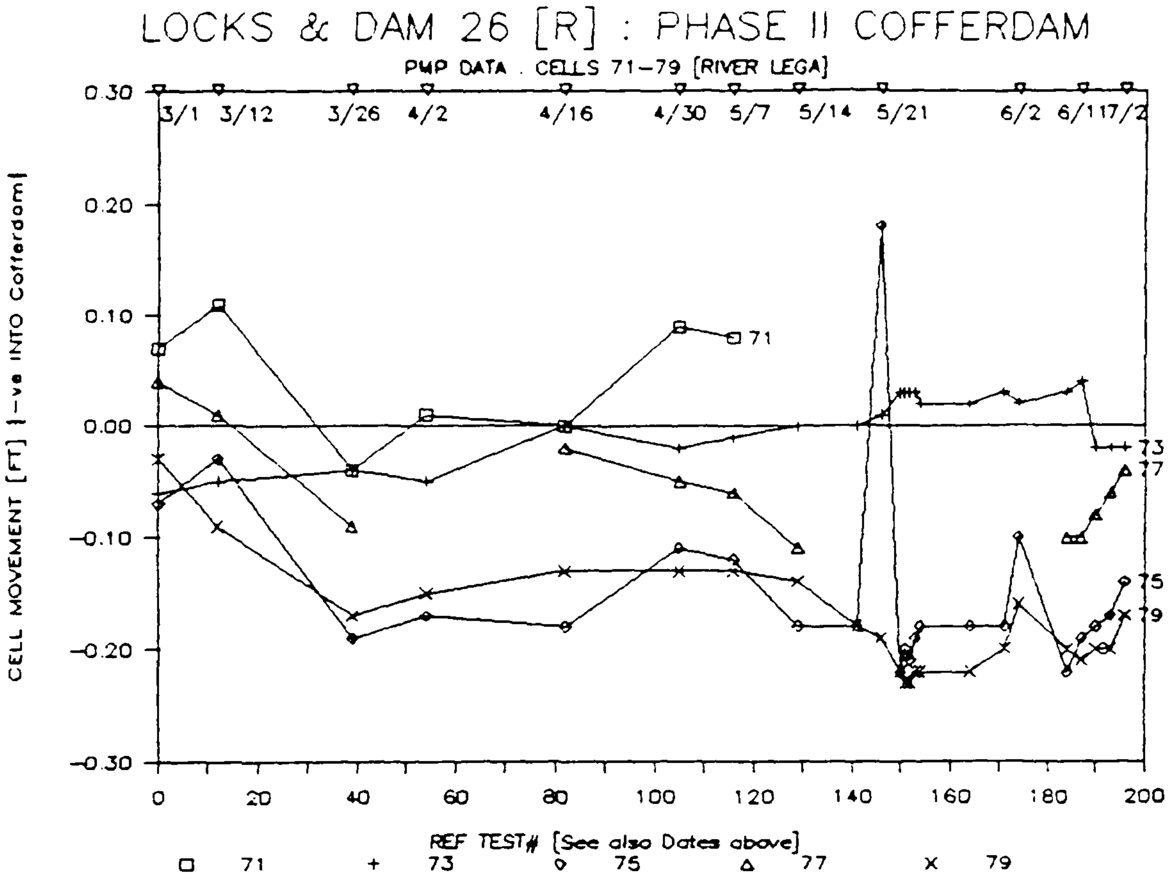


FIG 7.53 ATLAS MONITORING AVERAGE EVENTS PER HOUR

SP-78/79(HF), SP-79(LF), SP-79/80(LF) JANUARY-MARCH 1988



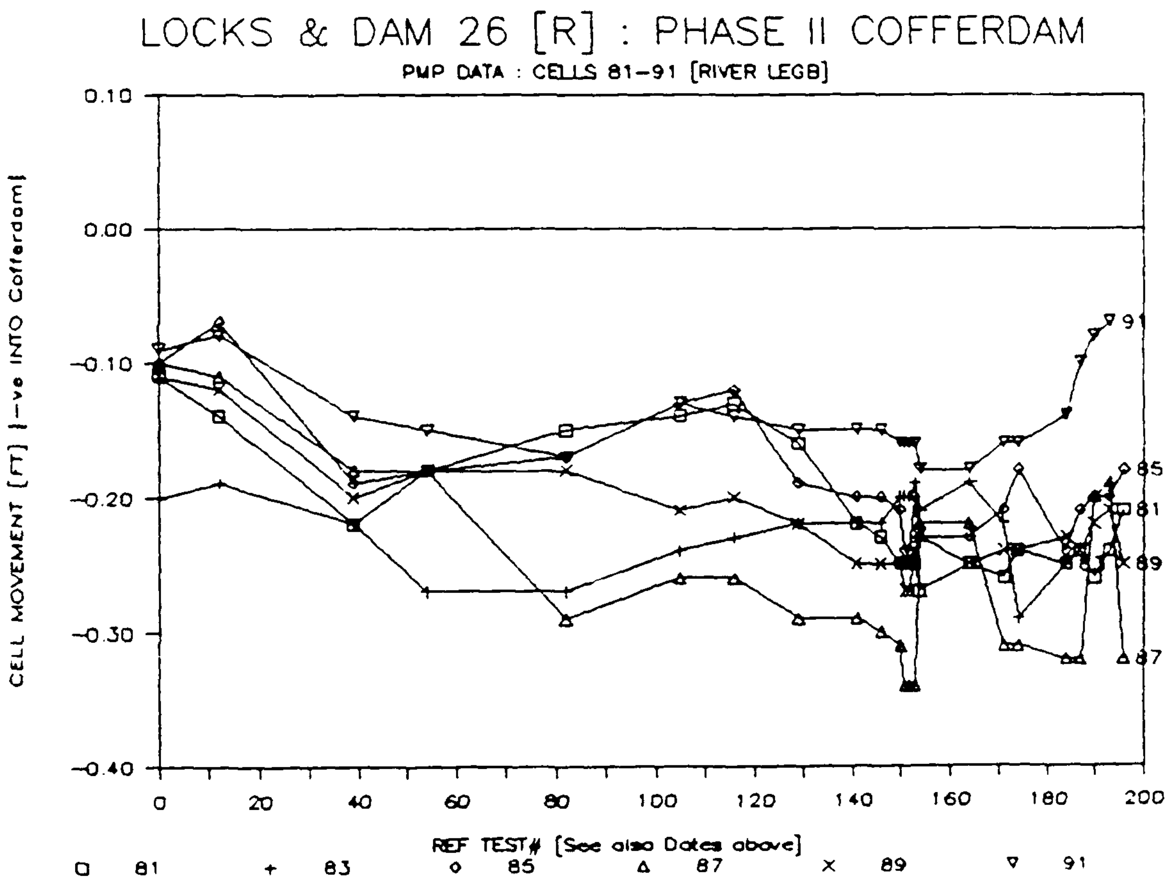
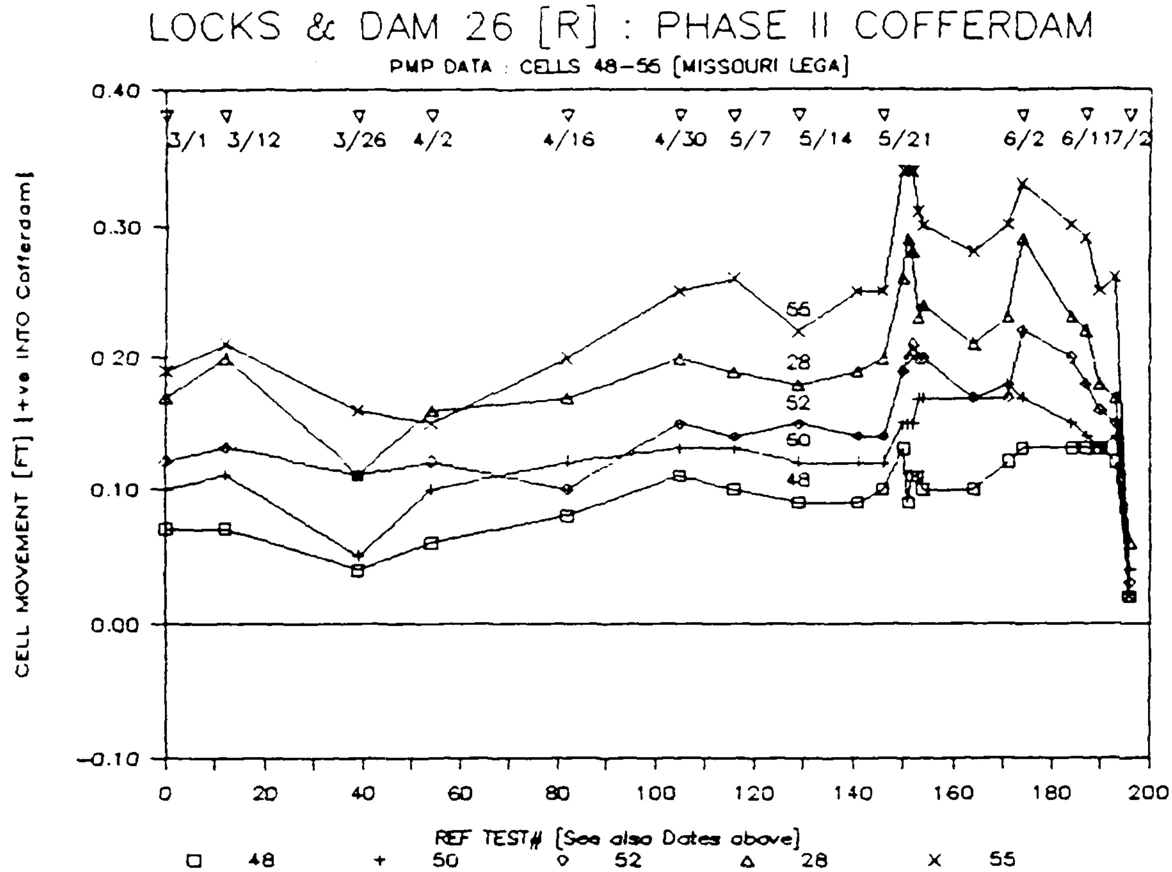


FIG 7.54 PILE MOVEMENT POINT DATA
CELLS 71–79 & 81–91 MARCH–JUNE 1986



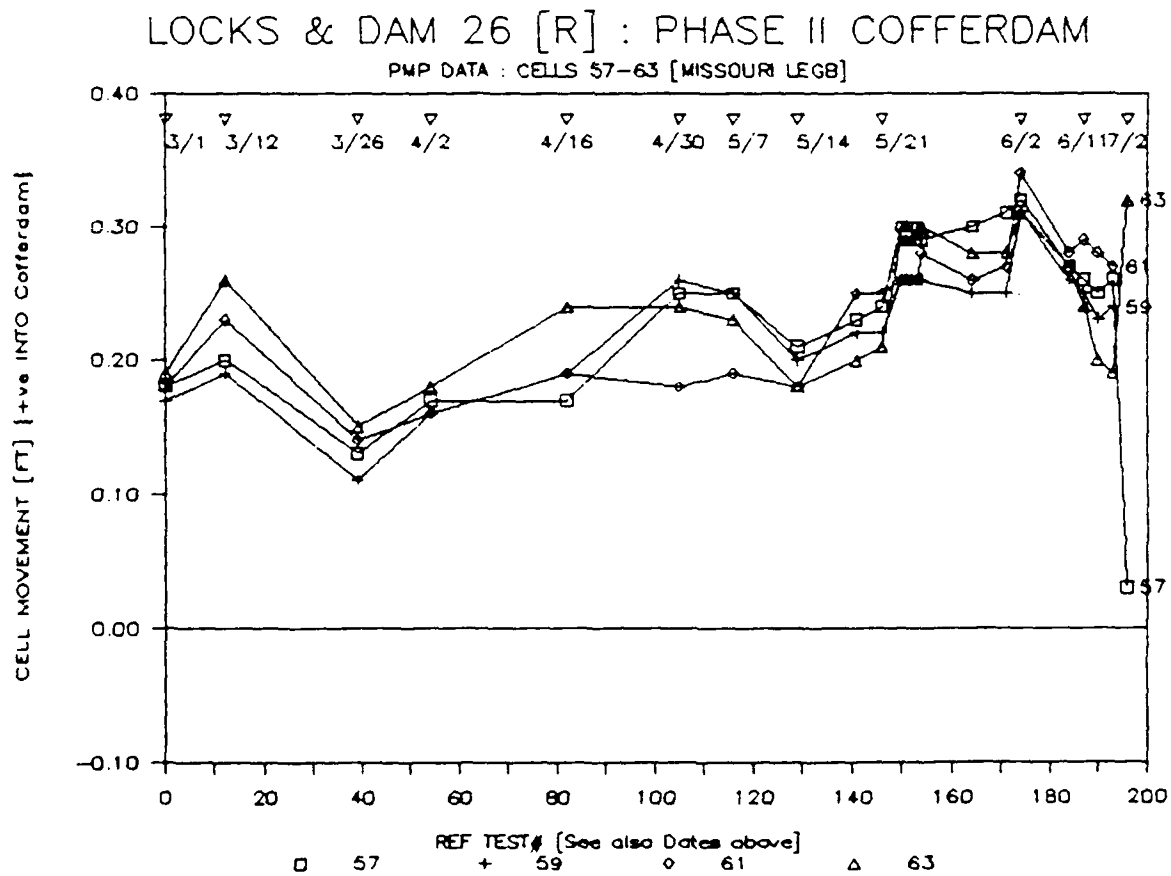


FIG 7.55 PILE MOVEMENT POINT DATA
CELLS 48-55 & 57-63 MARCH-JUNE 1986

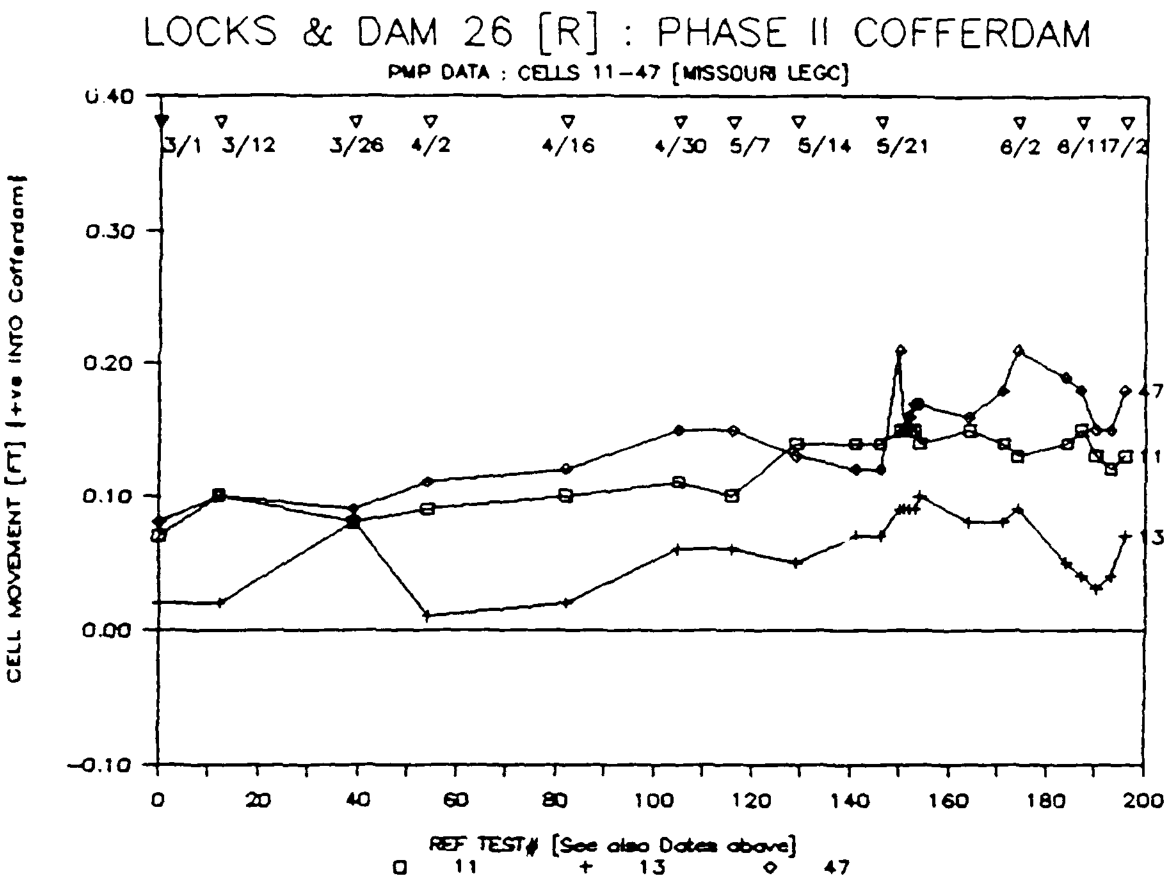
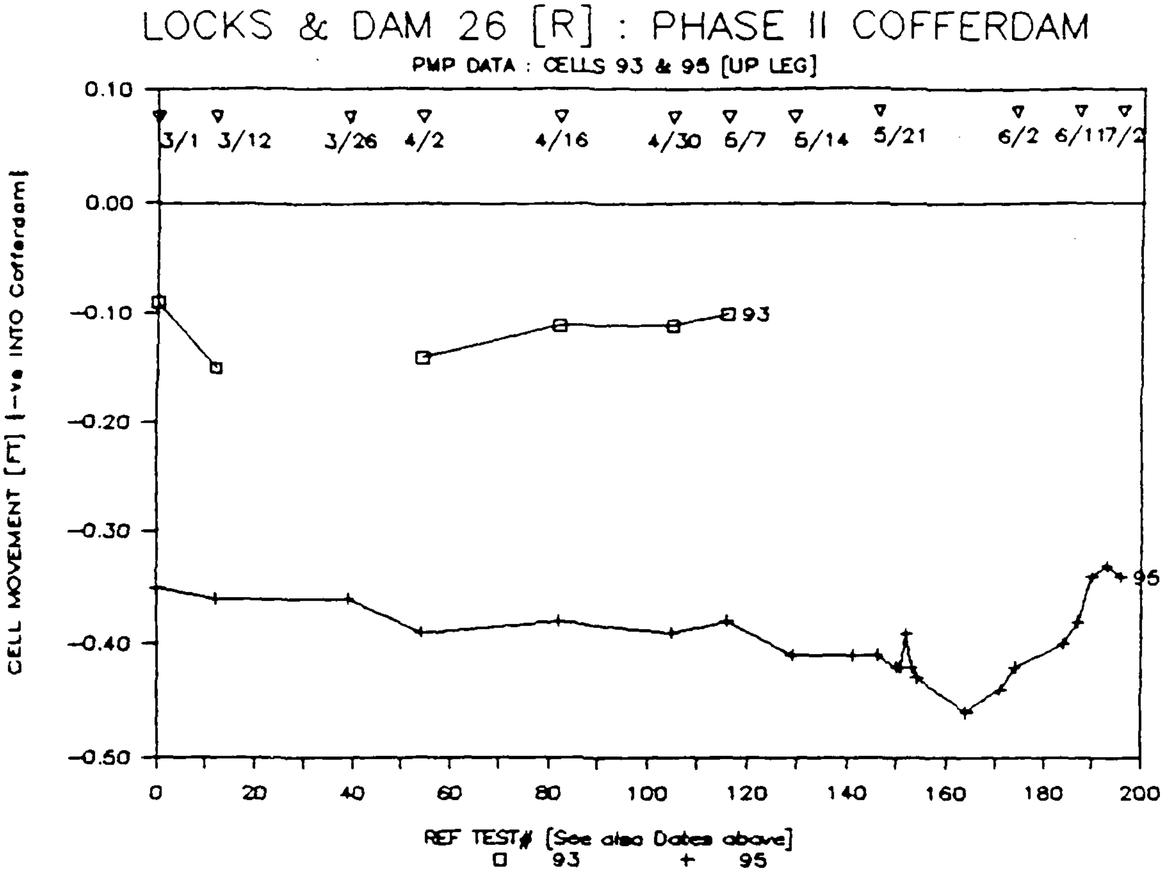


FIG 7.56 PILE MOVEMENT POINT DATA

CELLS 11-47

MARCH-JUNE 1986



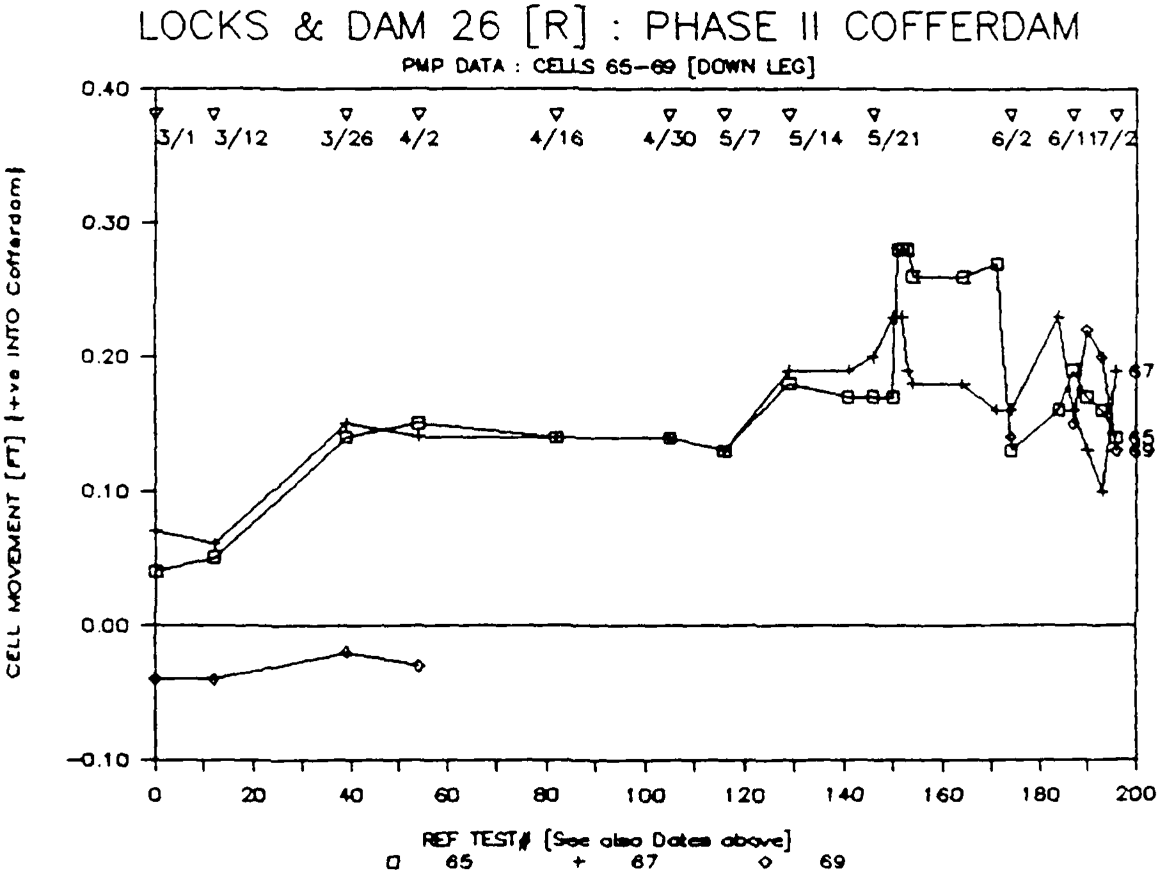
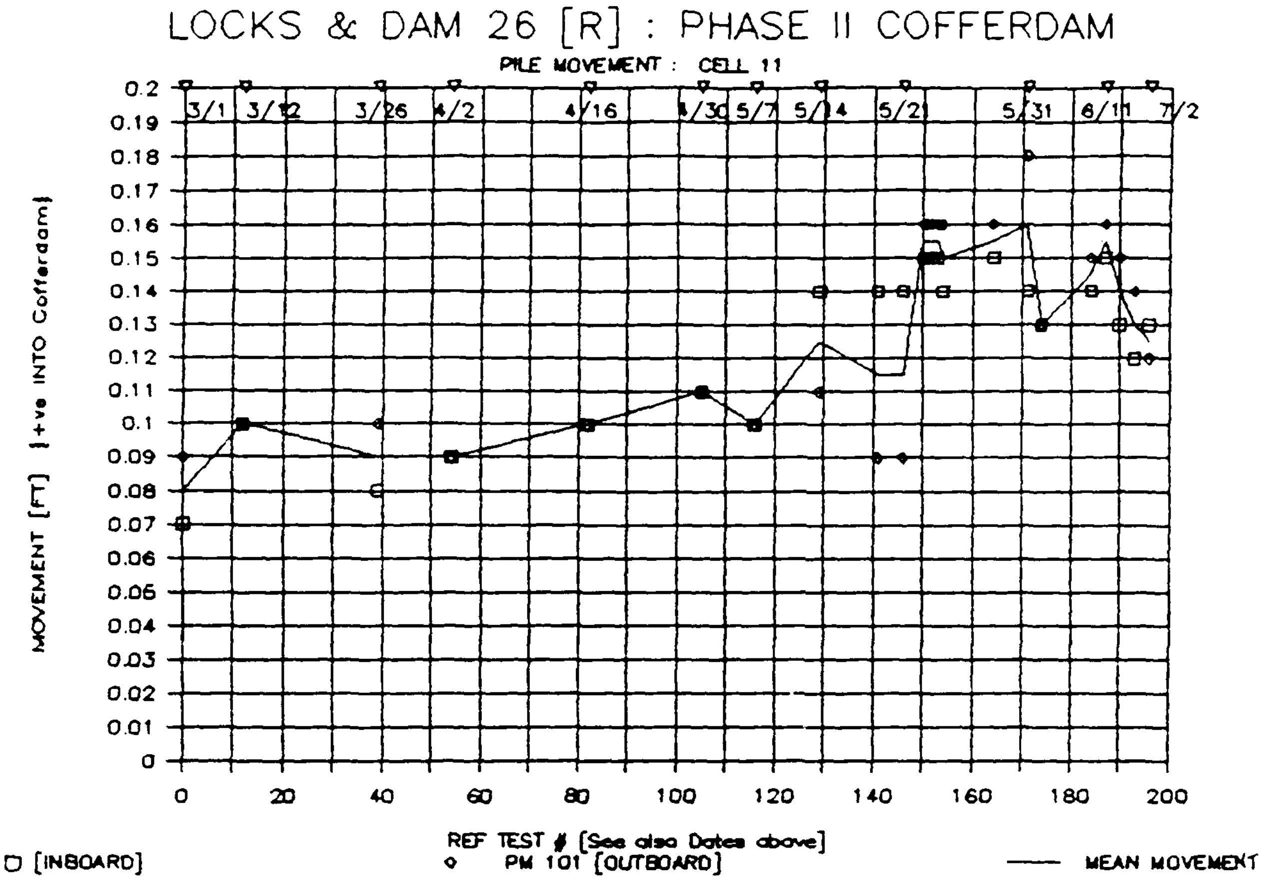


FIG 7.57 PILE MOVEMENT POINT DATA
CELLS 93, 95, 65-69 MARCH-JUNE 1986



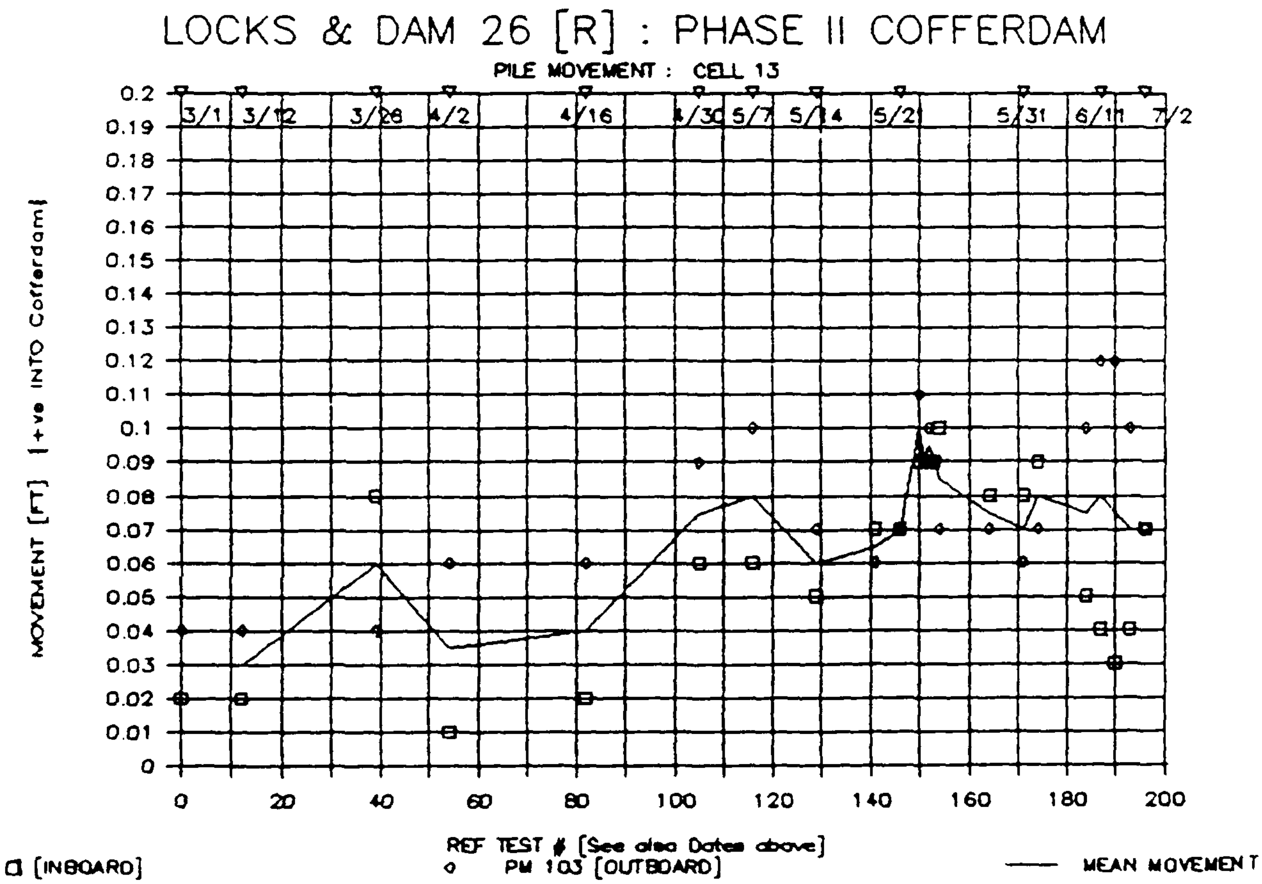
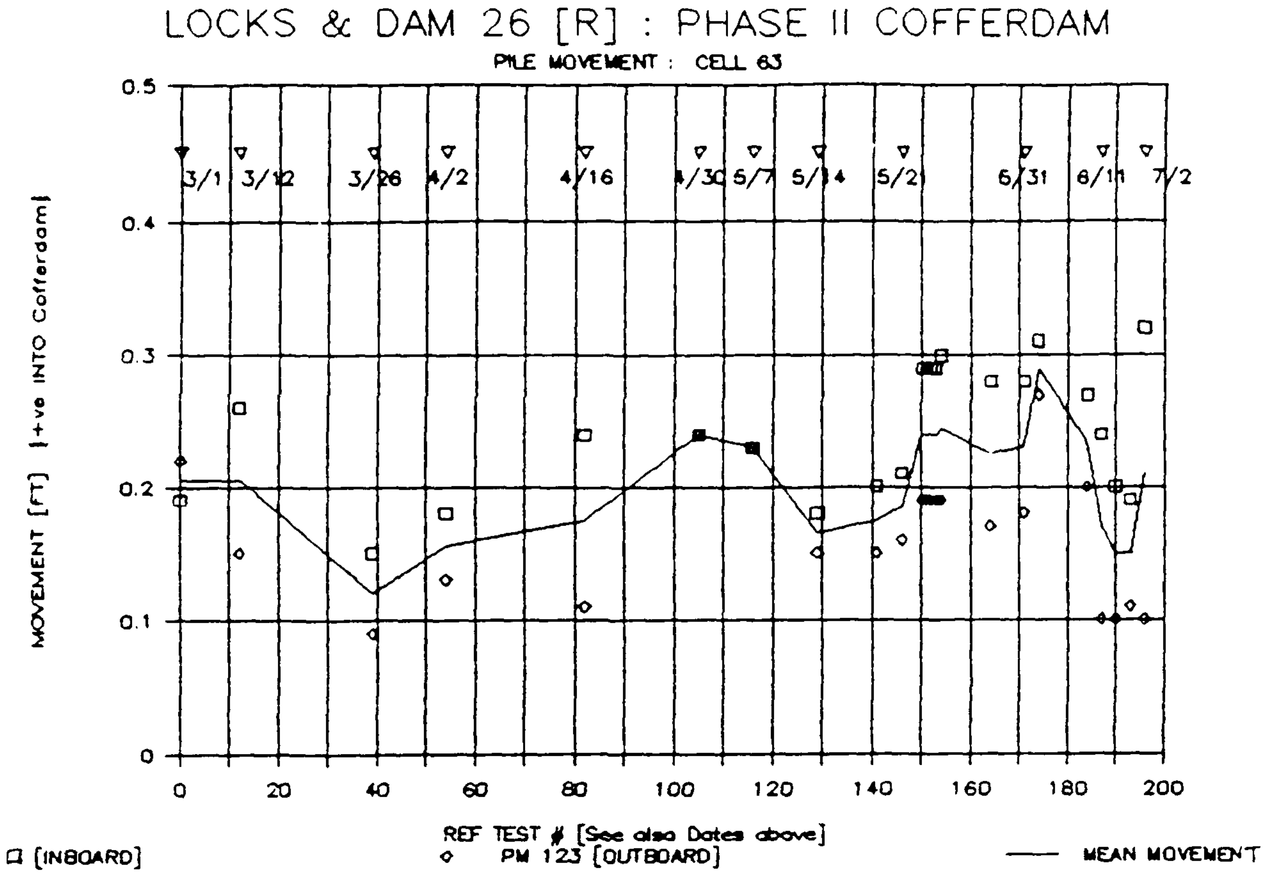


FIG. 7.58 PILE MOVEMENT POINT DATA
MEAN MOVEMENT CELLS 11 & 13 MARCH–JUNE 1986



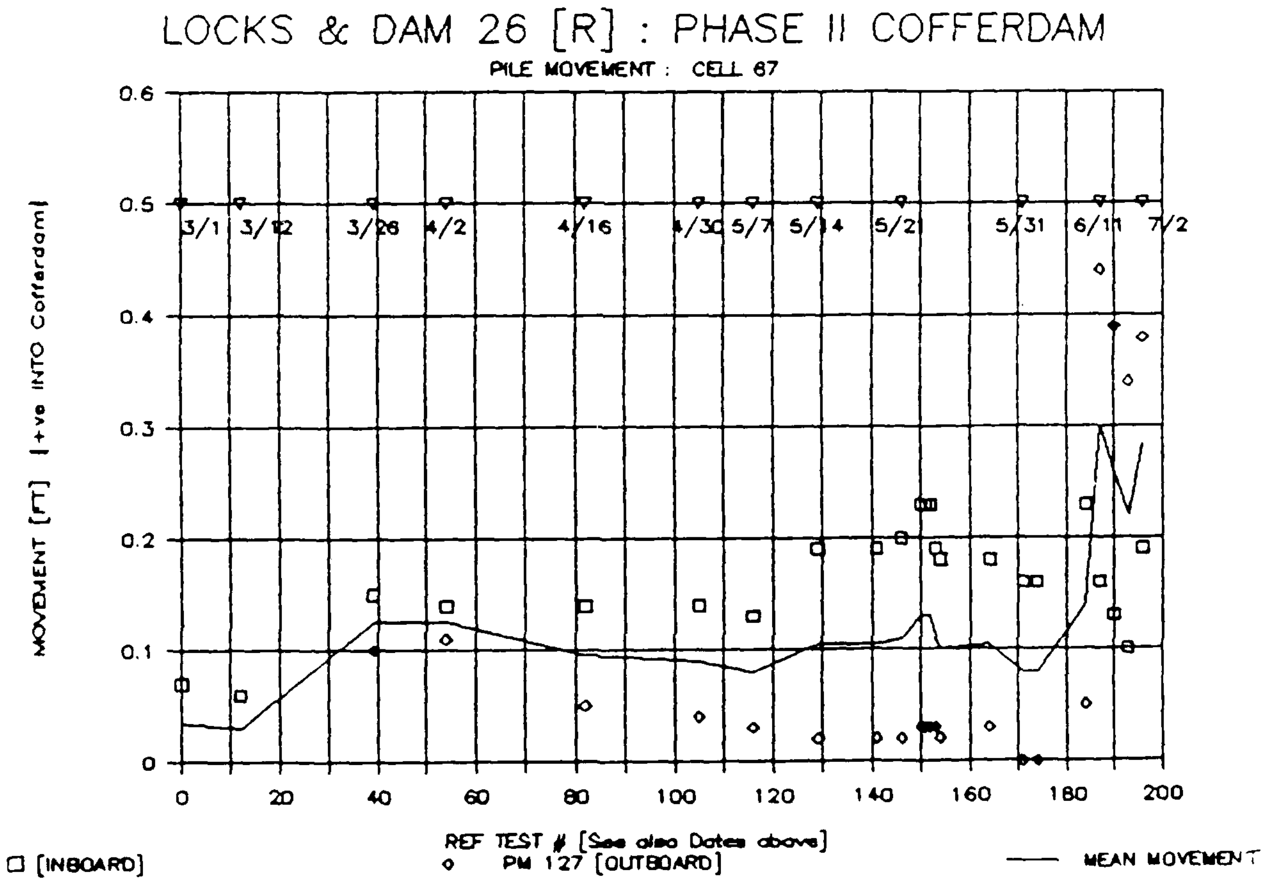
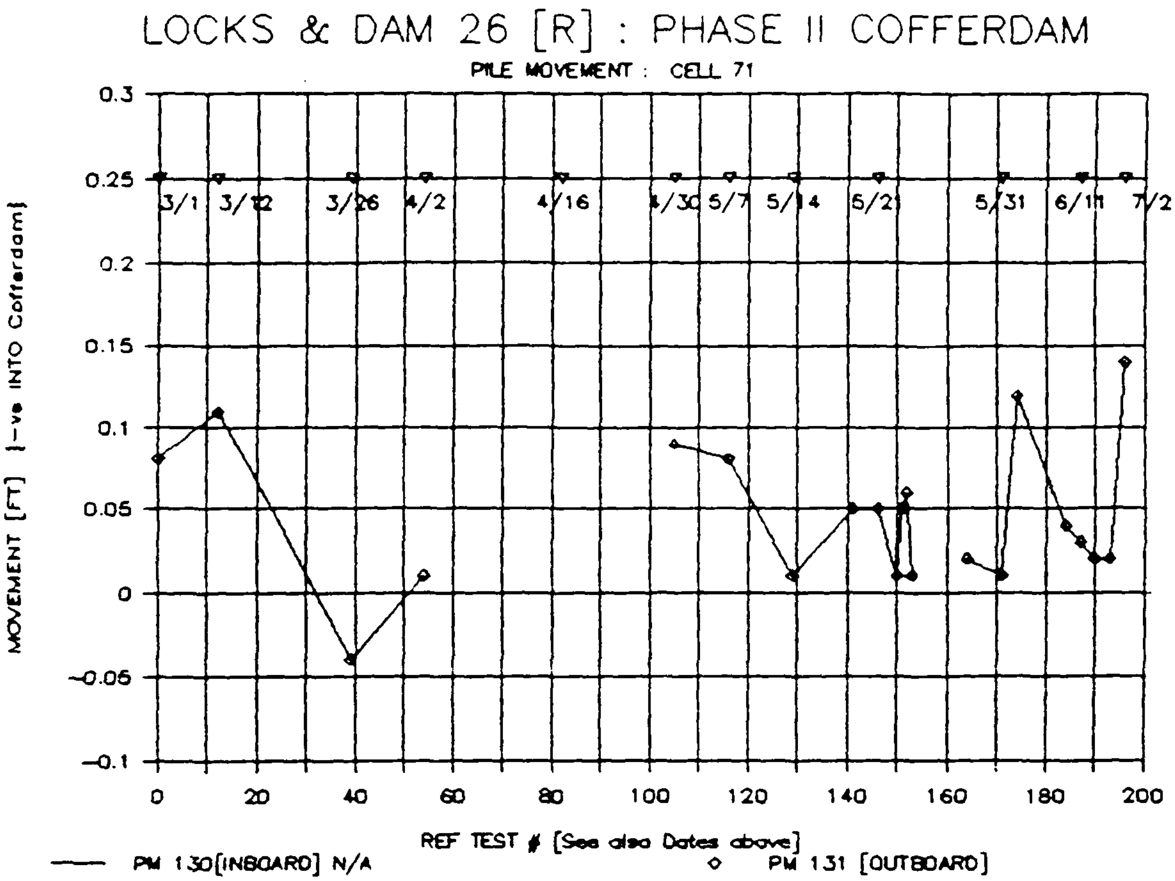


FIG 7.59 PILE MOVEMENT POINT DATA
MEAN MOVEMENT CELLS 63 & 67 MARCH-JUNE 1986



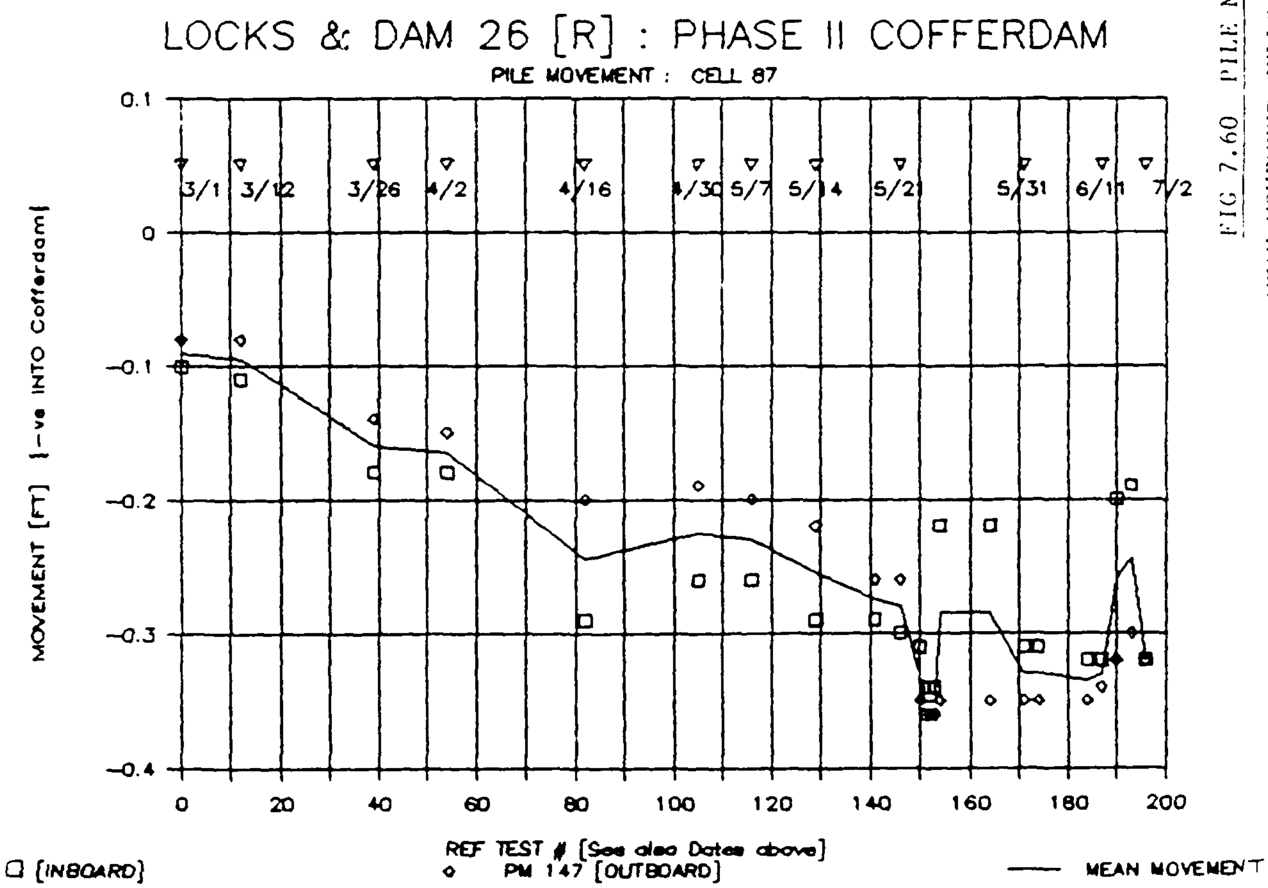


FIG 7.60 PILE MOVEMENT POINT DATA

MEAN MOVEMENT CELLS 71 & 87 MARCH-JUNE 1986

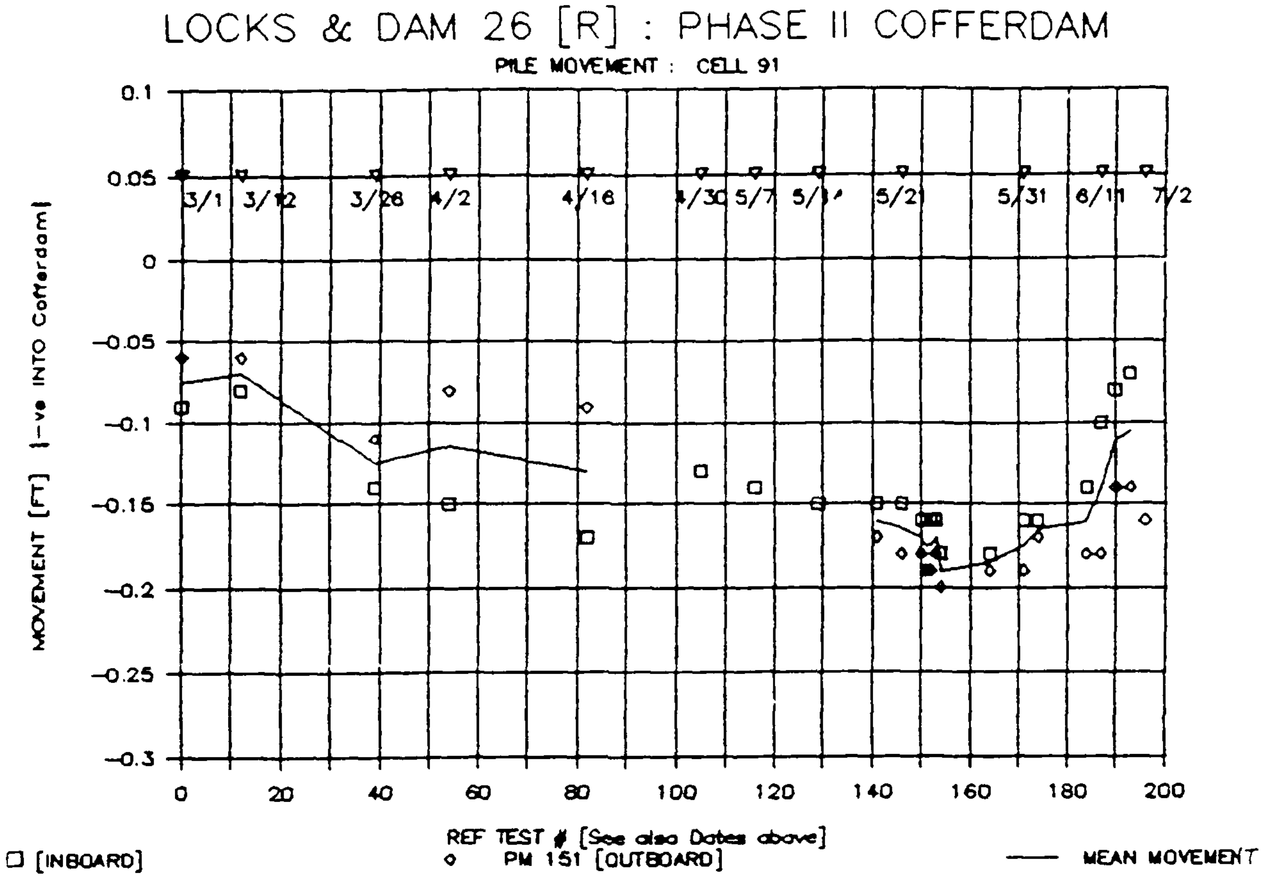
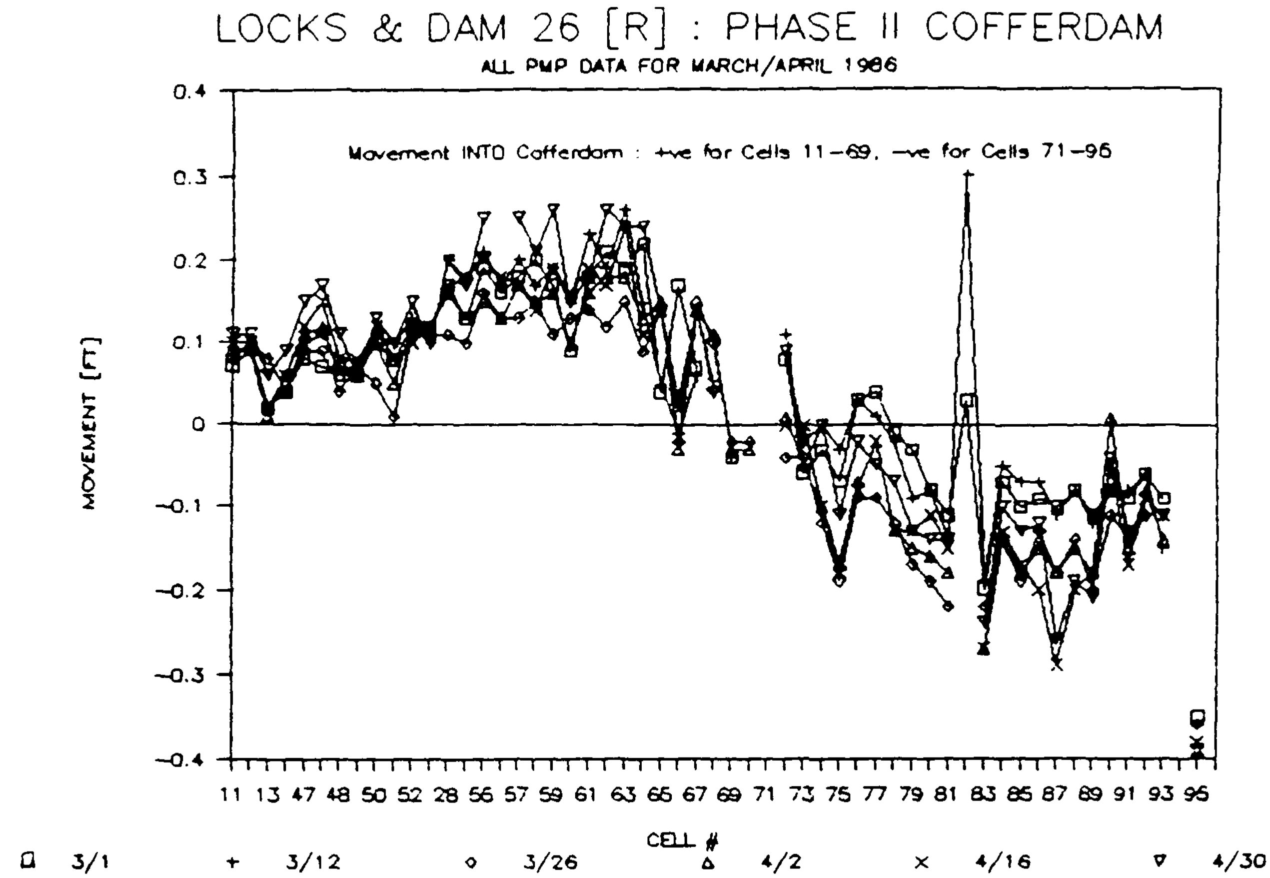


FIG 7.61 PILE MOVEMENT POINT DATA

MEAN MOVEMENT CELL 91

MARCH-JUNE 1986



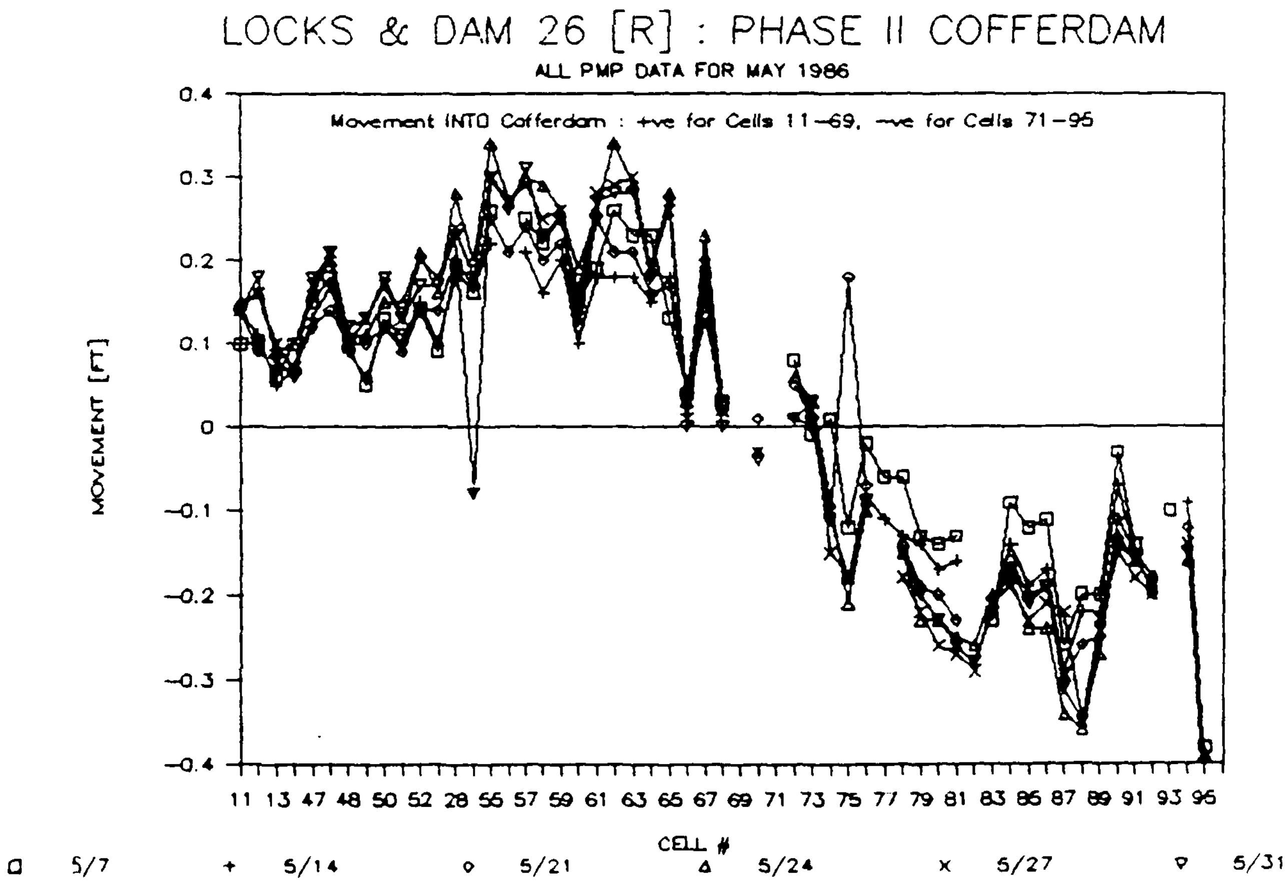
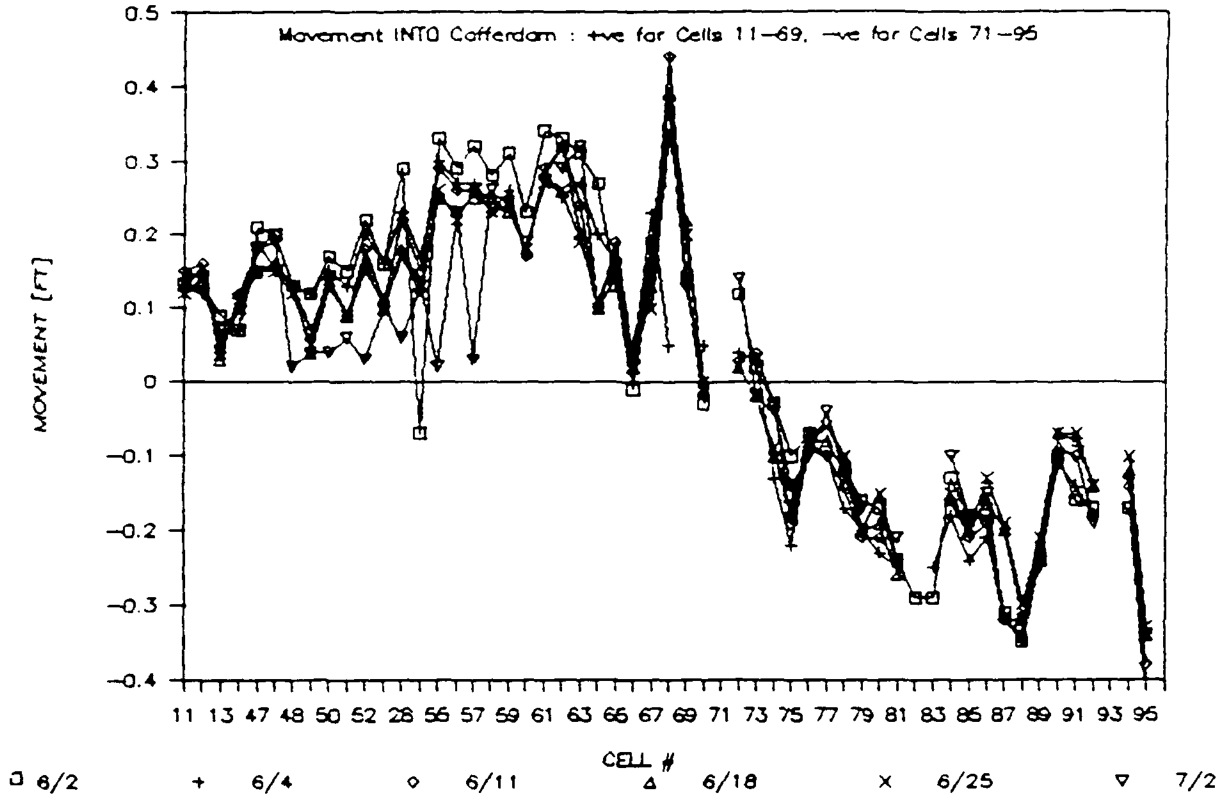


FIG 7.62 PILE MOVEMENT POINT DATA
ALL DATA MARCH-APRIL-MAY 1986

LOCKS & DAM 26 [R] : PHASE II COFFERDAM

ALL PMP DATA FOR JUNE 1986



LOCKS & DAM 26 [R] : PHASE II COFFERDAM

ALL PMP DATA FOR AUGUST 1986

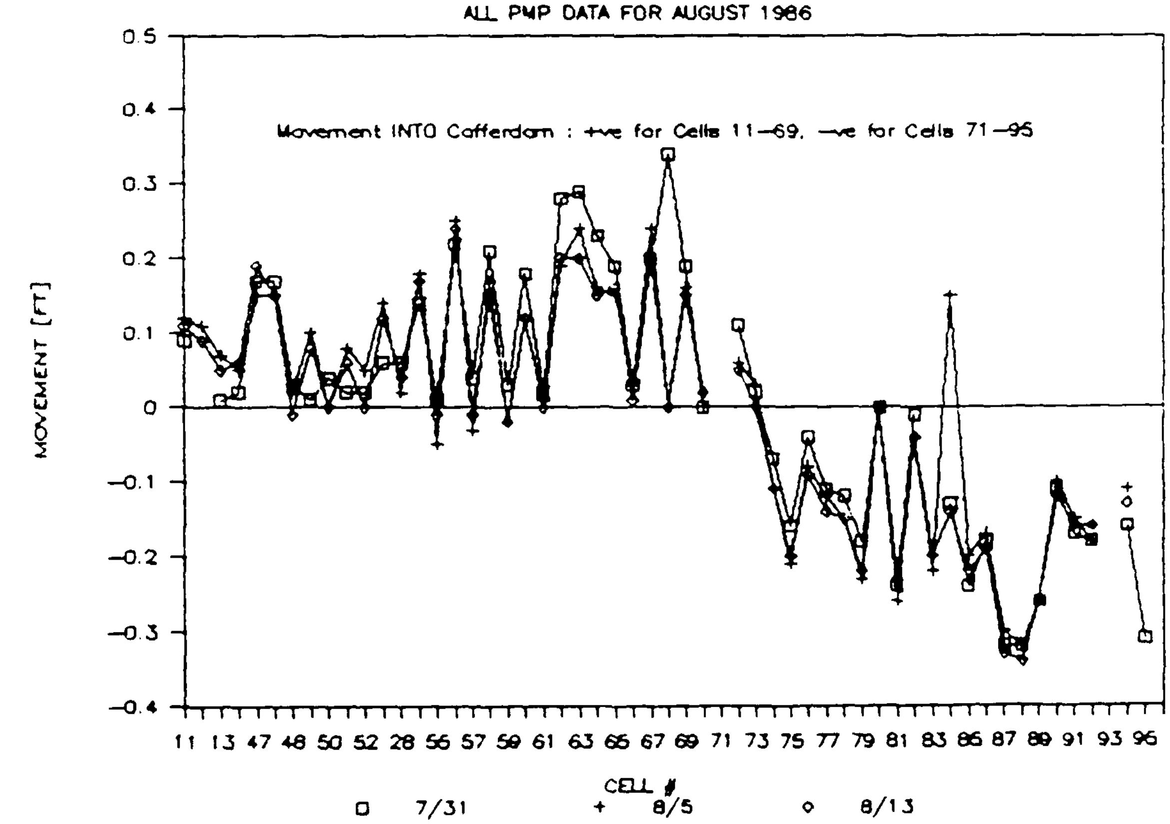


FIG 7.63 PILE MOVEMENT POINT DATA
ALL DATA JUNE & AUGUST 1986

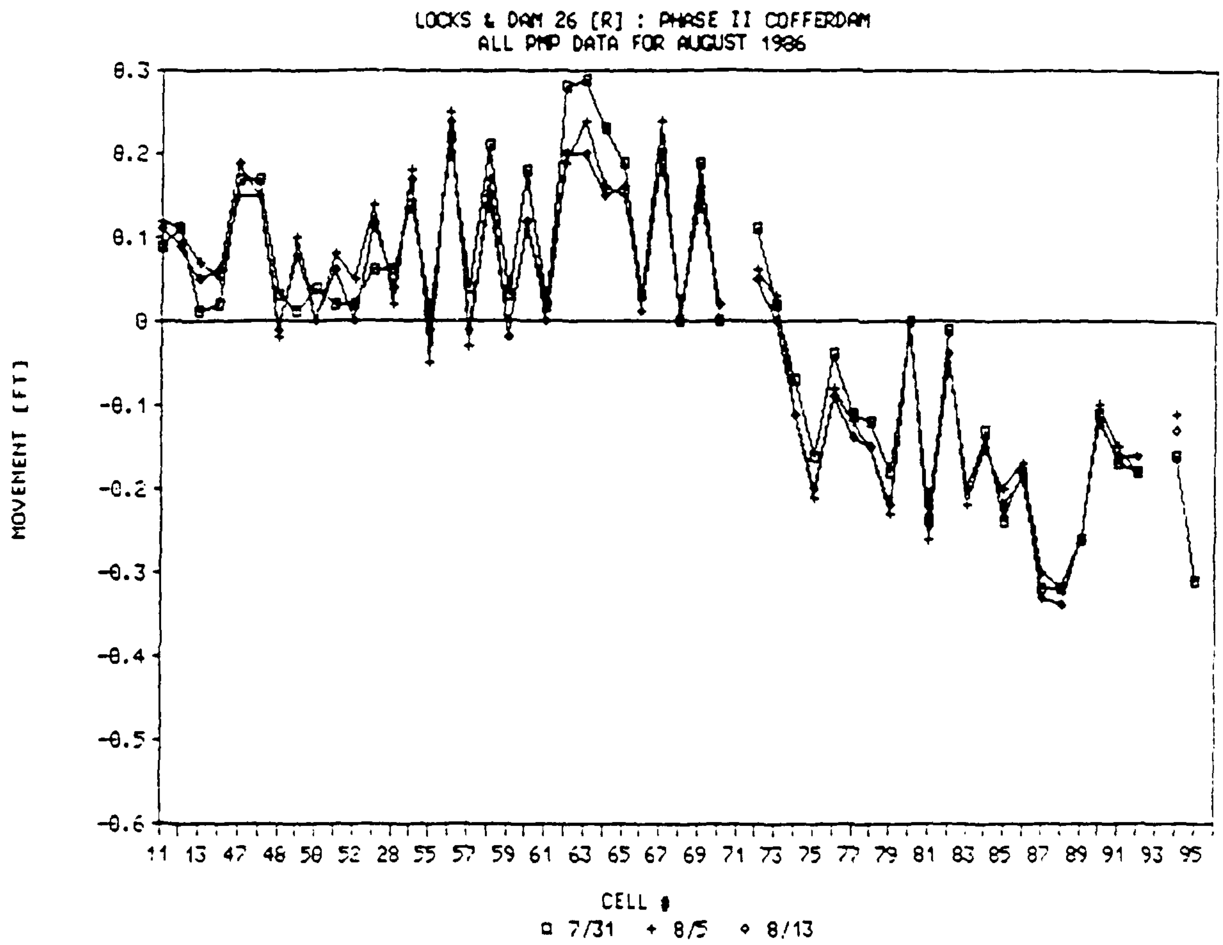


FIG 7.64 PILE MOVEMENT POINT DATA

ALL DATA AUGUST 1986

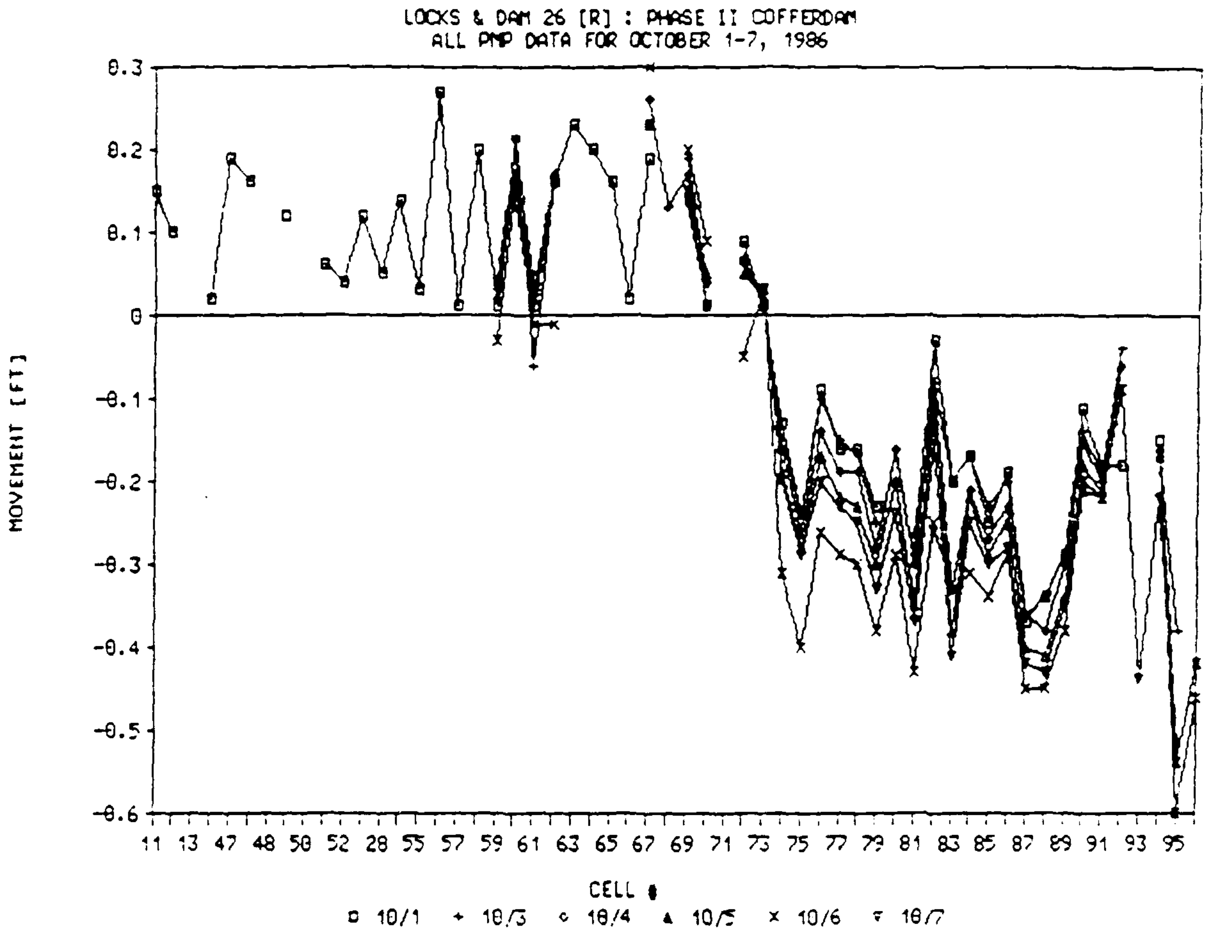


FIG 7.65 PILE MOVEMENT POINT DATA

ALL DATA OCTOBER 1-7, 1986

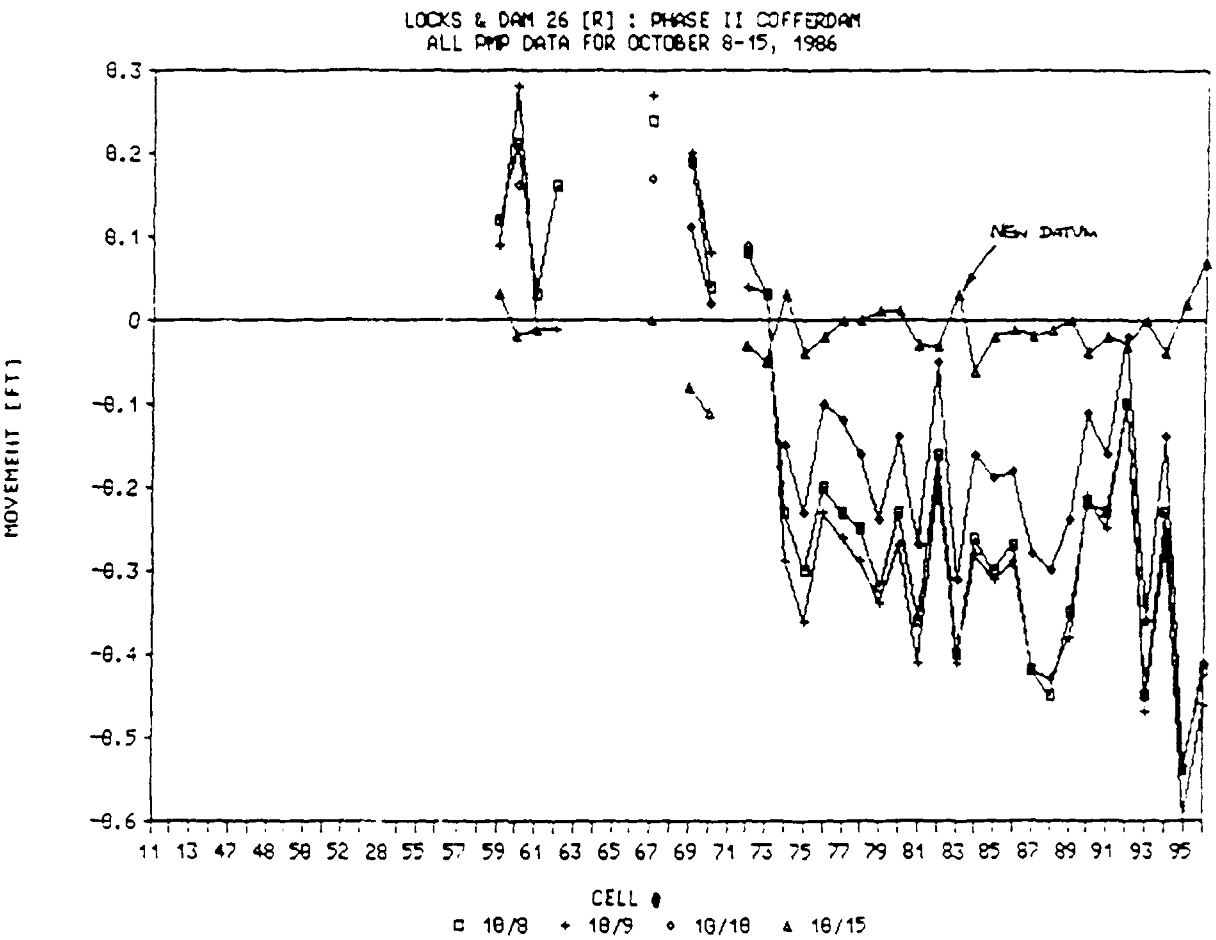
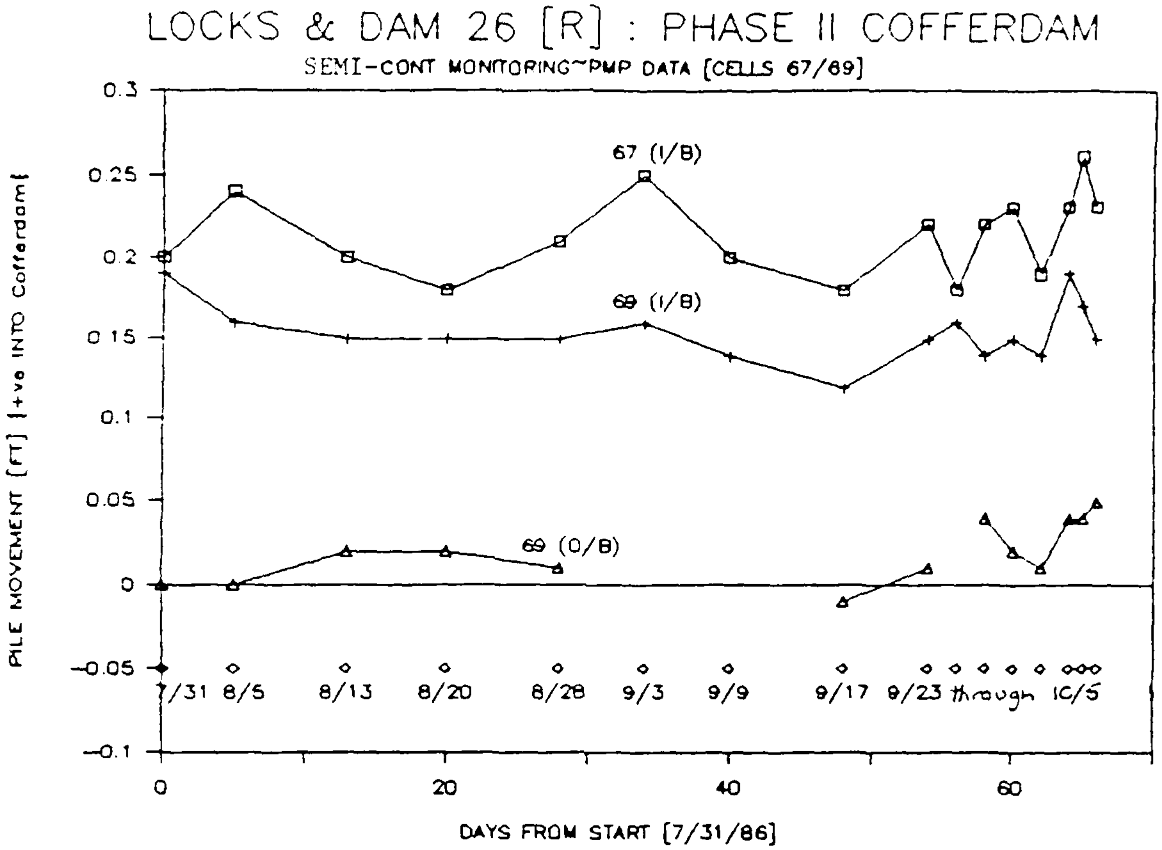


FIG 7.66 PILE MOVEMENT POINT DATA

ALL DATA OCTOBER 8-15, 1986



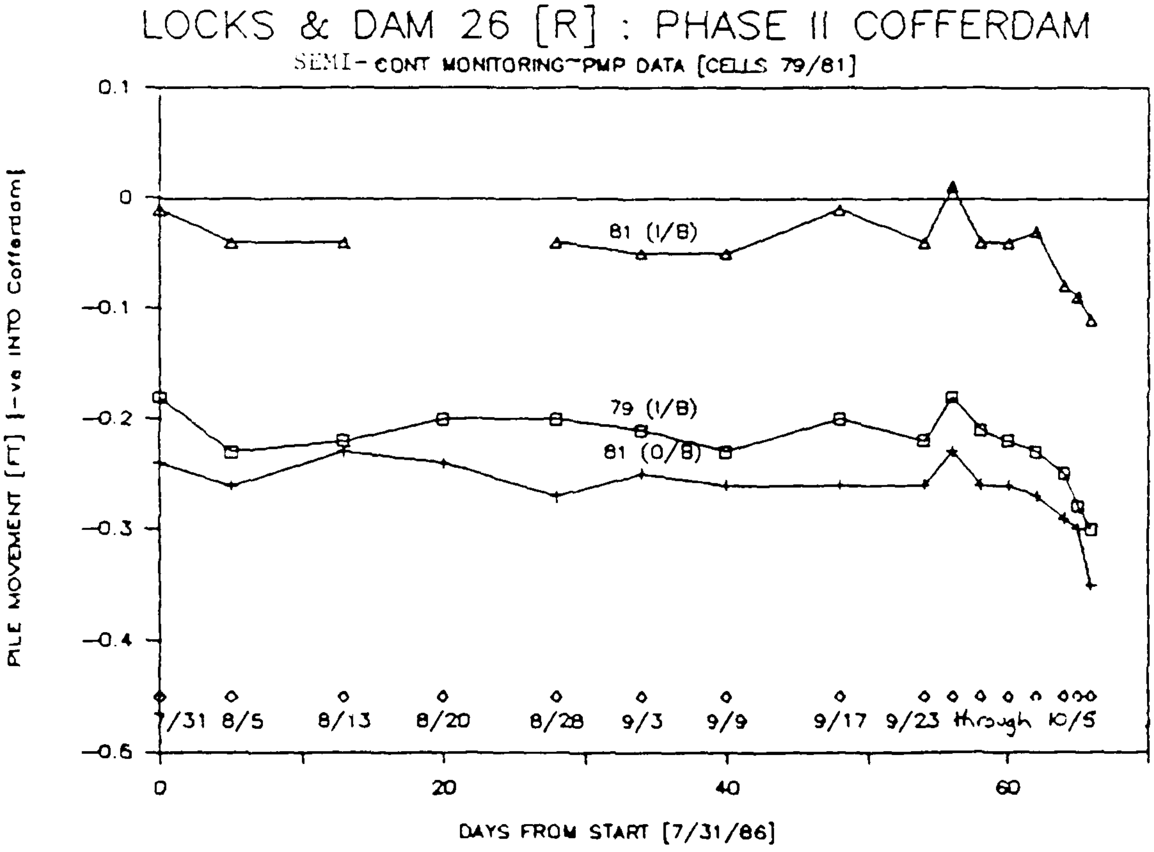
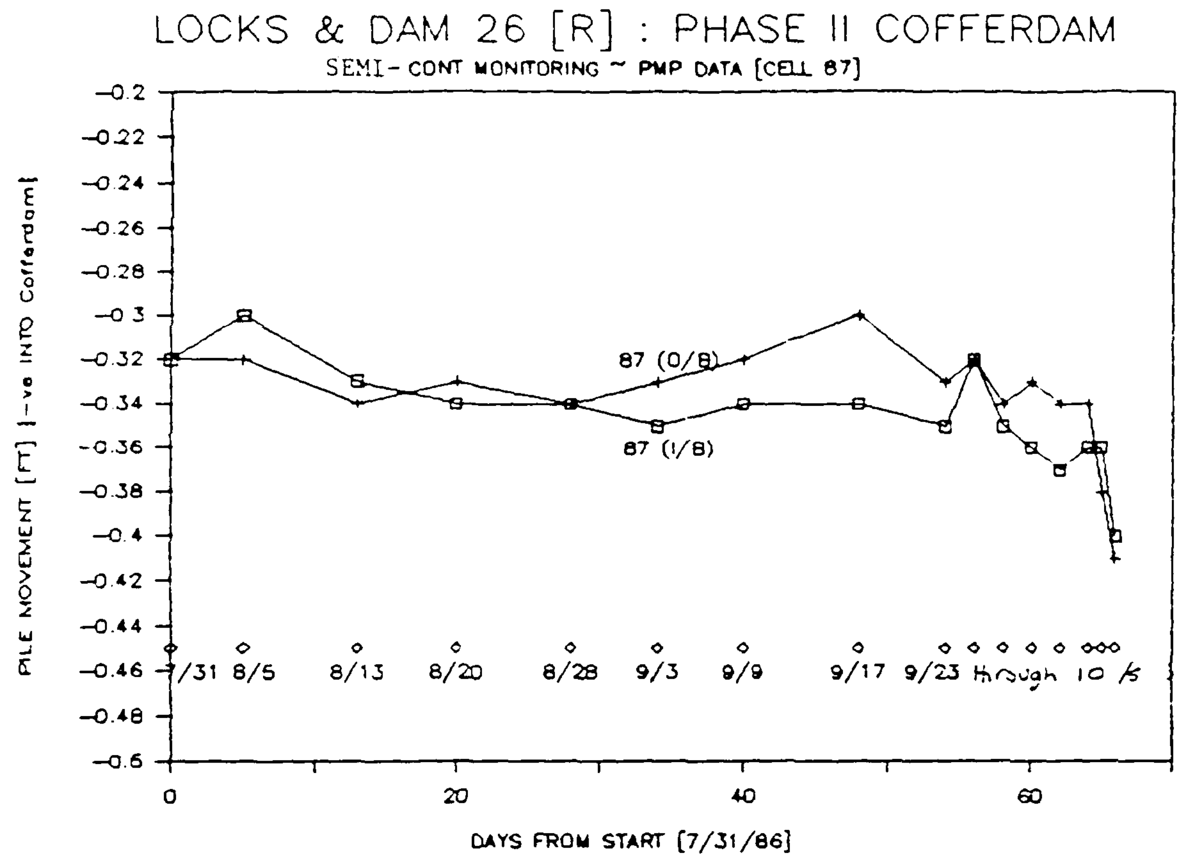


FIG 7.67 PILE MOVEMENT POINT DATA
CELLS 67, 69, 79 & 81 AUGUST-OCTOBER 1986



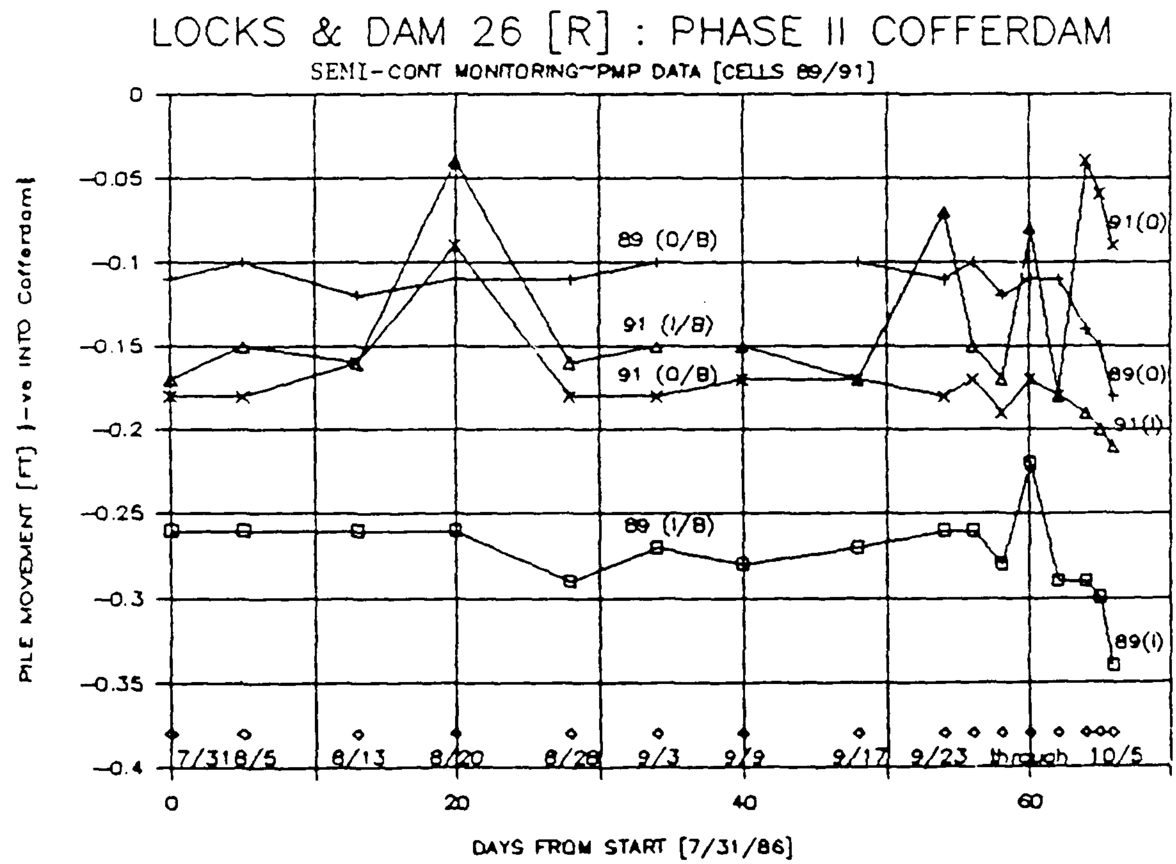


FIG. 7.68 PILE MOVEMENT POINT DATA
CELLS 87, 89 & 91 AUGUST-OCTOBER 1986

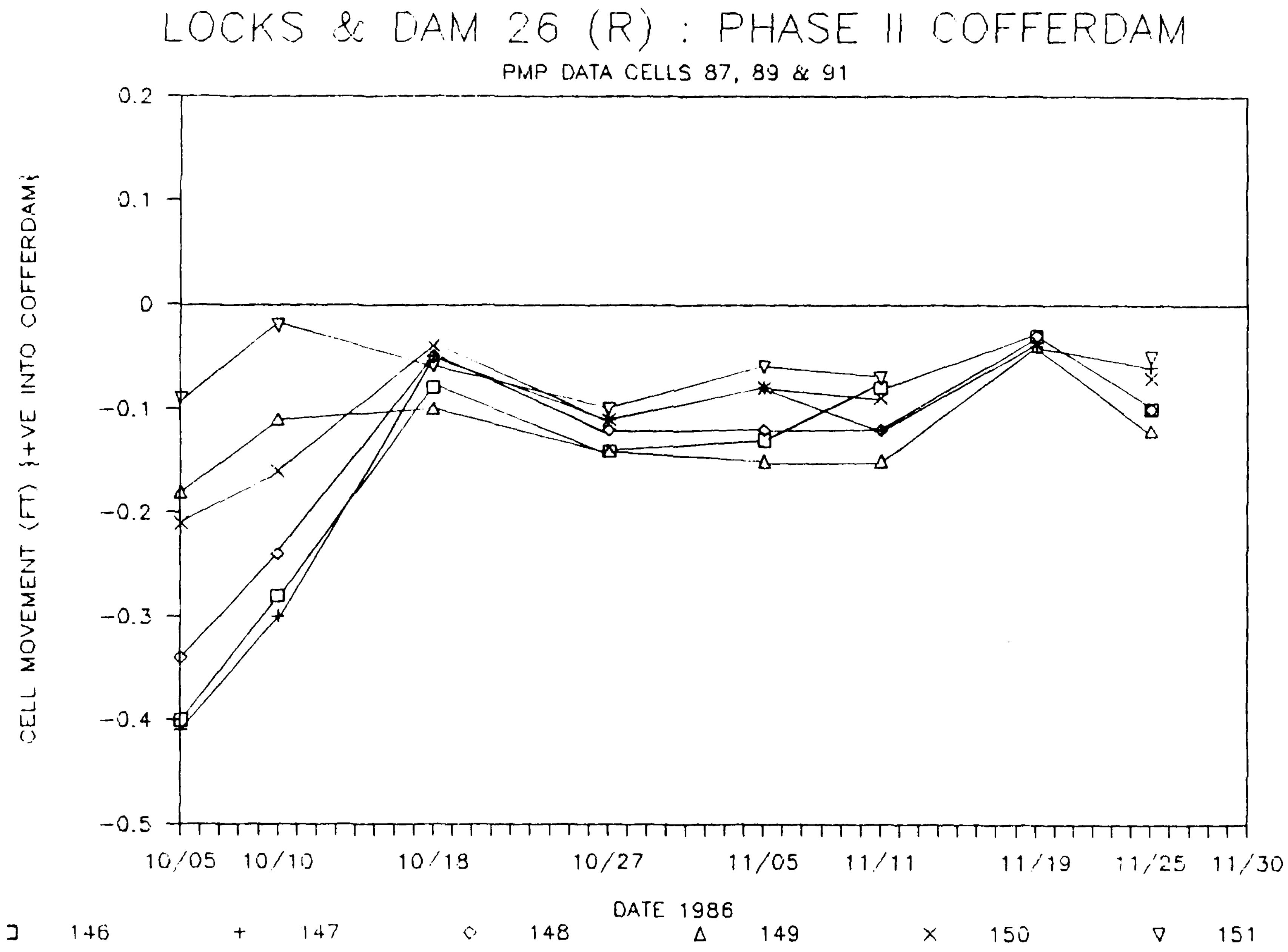


FIG 7.69 PILE MOVEMENT POINT DATA

CELLS 87, 89 & 91 OCTOBER-NOVEMBER 1986

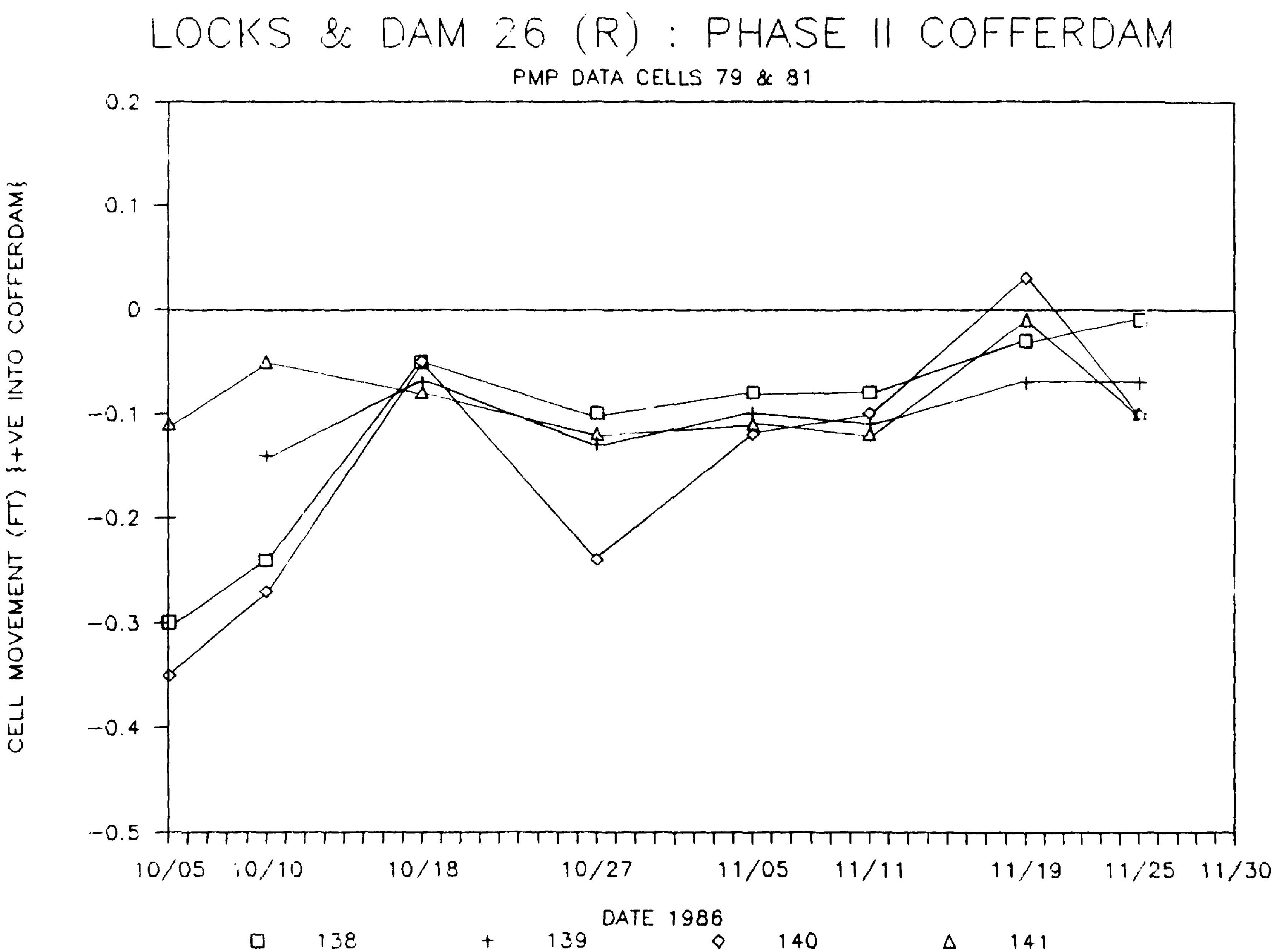


FIG 7.70 PILE MOVEMENT POINT DATA

CELLS 79 & 81 OCTOBER-NOVEMBER 1986

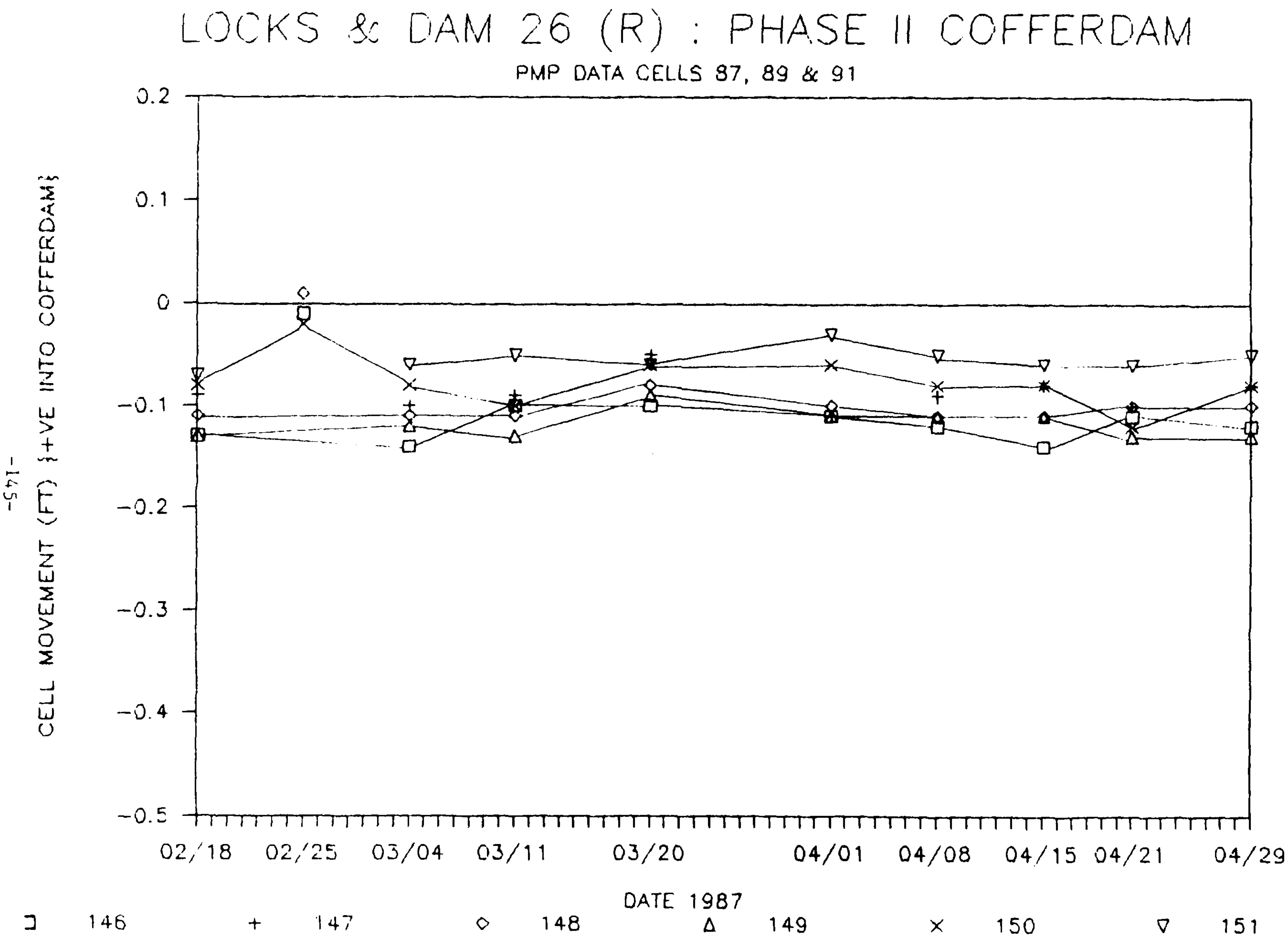


FIG 7.71 PILE MOVEMENT POINT DATA

CELLS 87, 89 & 91 FEBRUARY-APRIL 1987

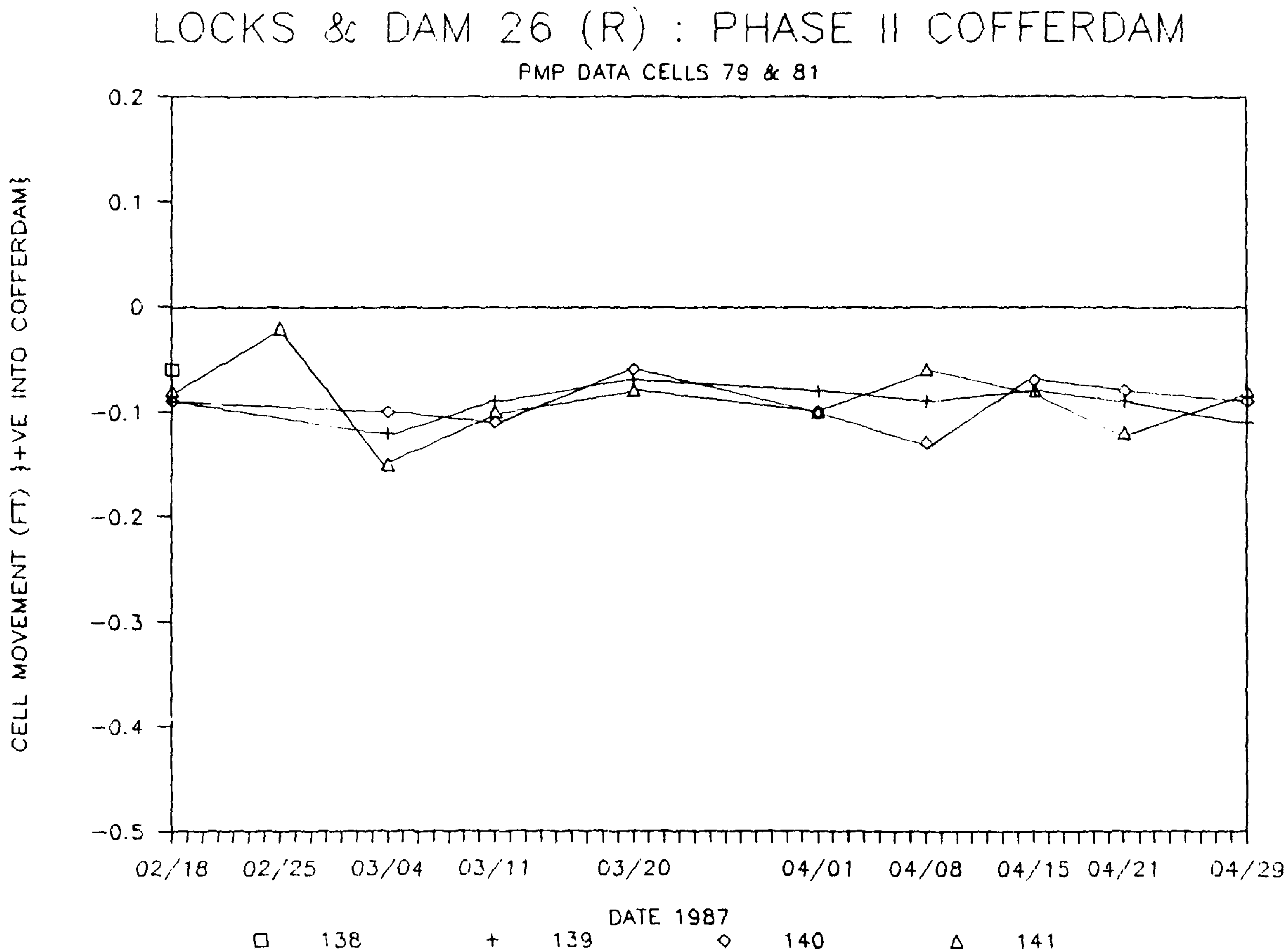


FIG 7.72 PILE MOVEMENT POINT DATA

CELLS 79 & 81 FEBRUARY-APRIL 1987

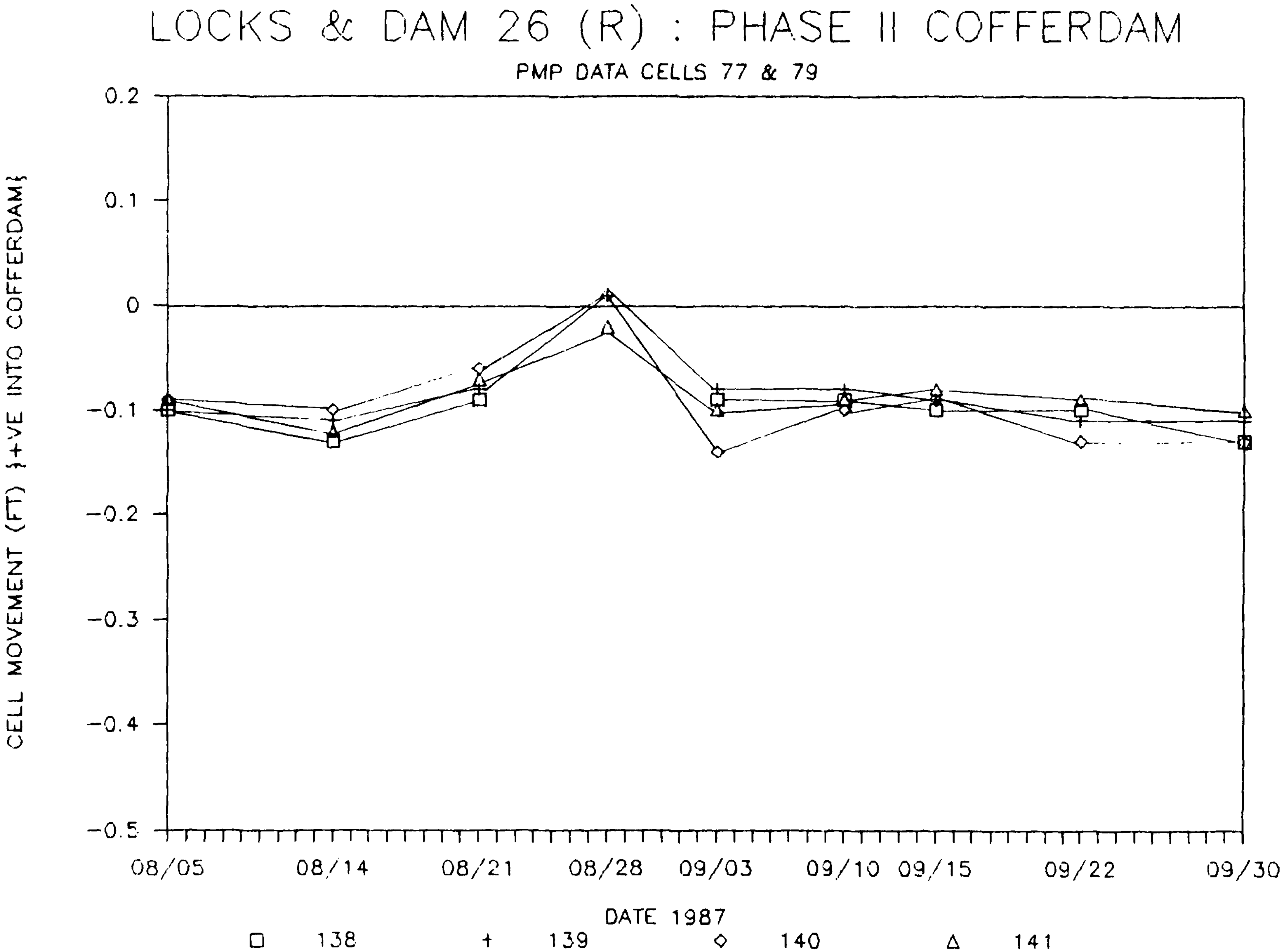


FIG 7.73 PILE MOVEMENT POINT DATA

CELLS 77 & 79 AUGUST-SEPTEMBER 1987

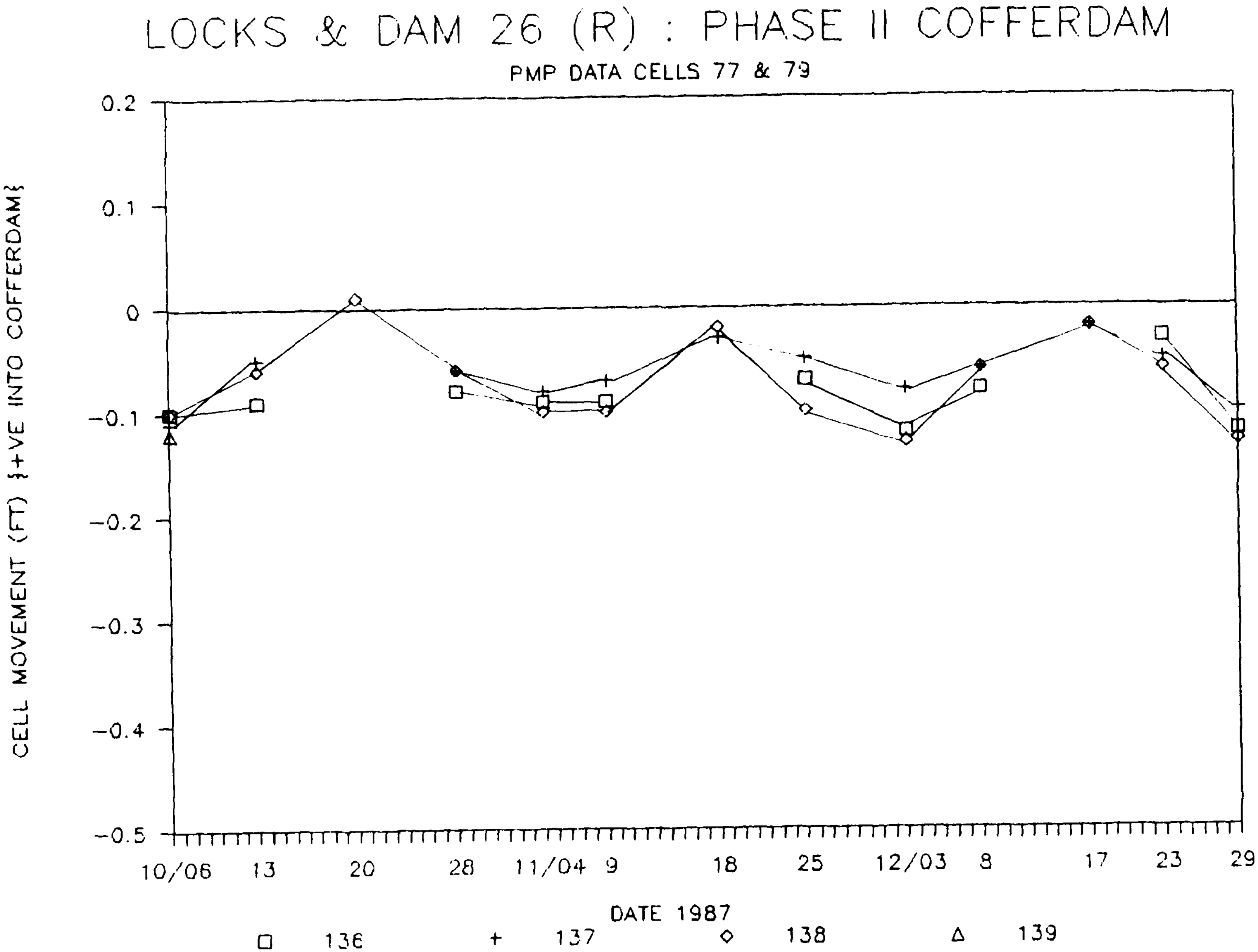


FIG 7.74 PILE MOVEMENT POINT DATA

CELLS 77 & 79 OCTOBER-DECEMBER 1987

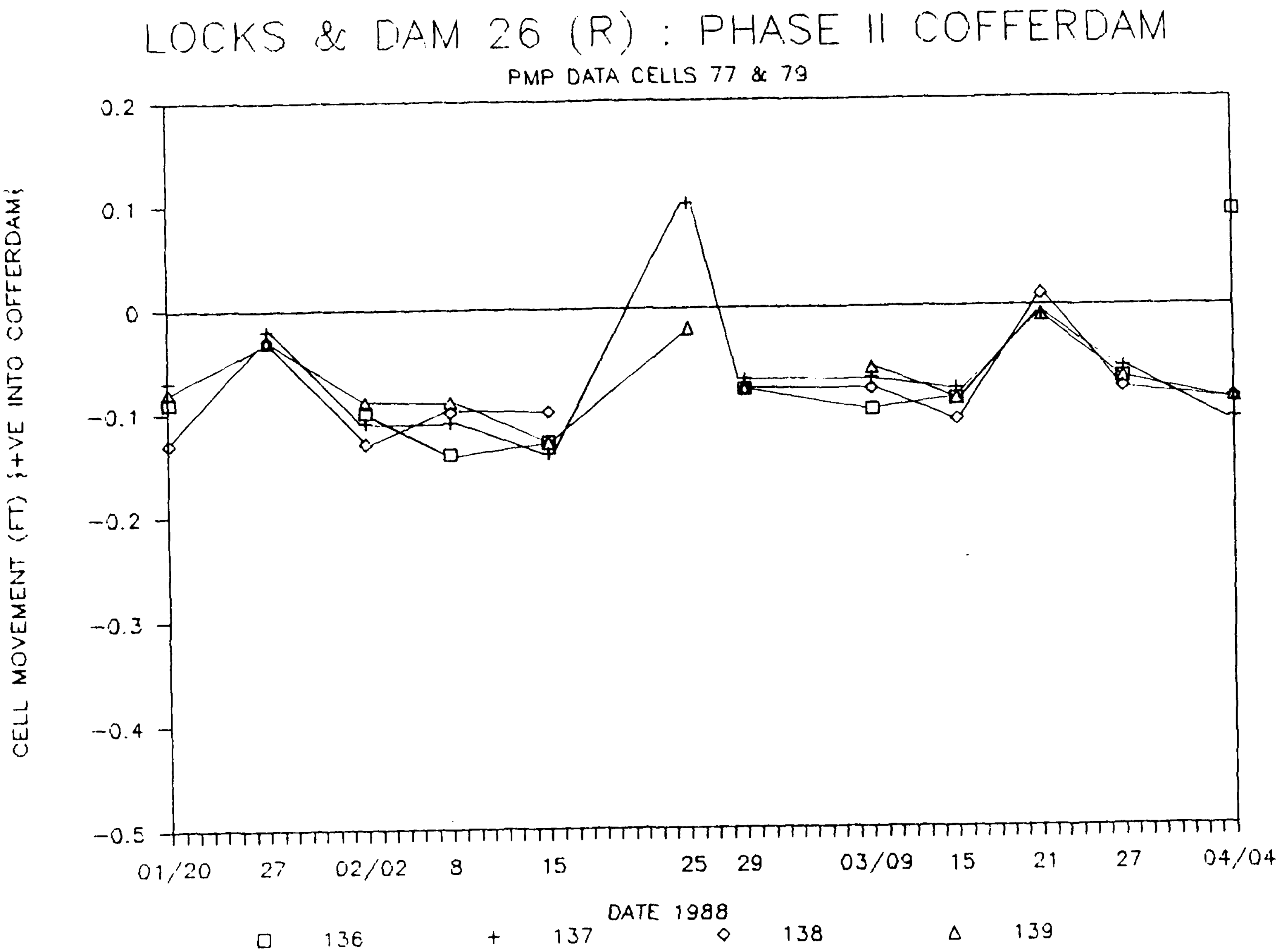


FIG 7.75 PILE MOVEMENT POINT DATA

CELLS 77 & 79 JANUARY-APRIL 1988

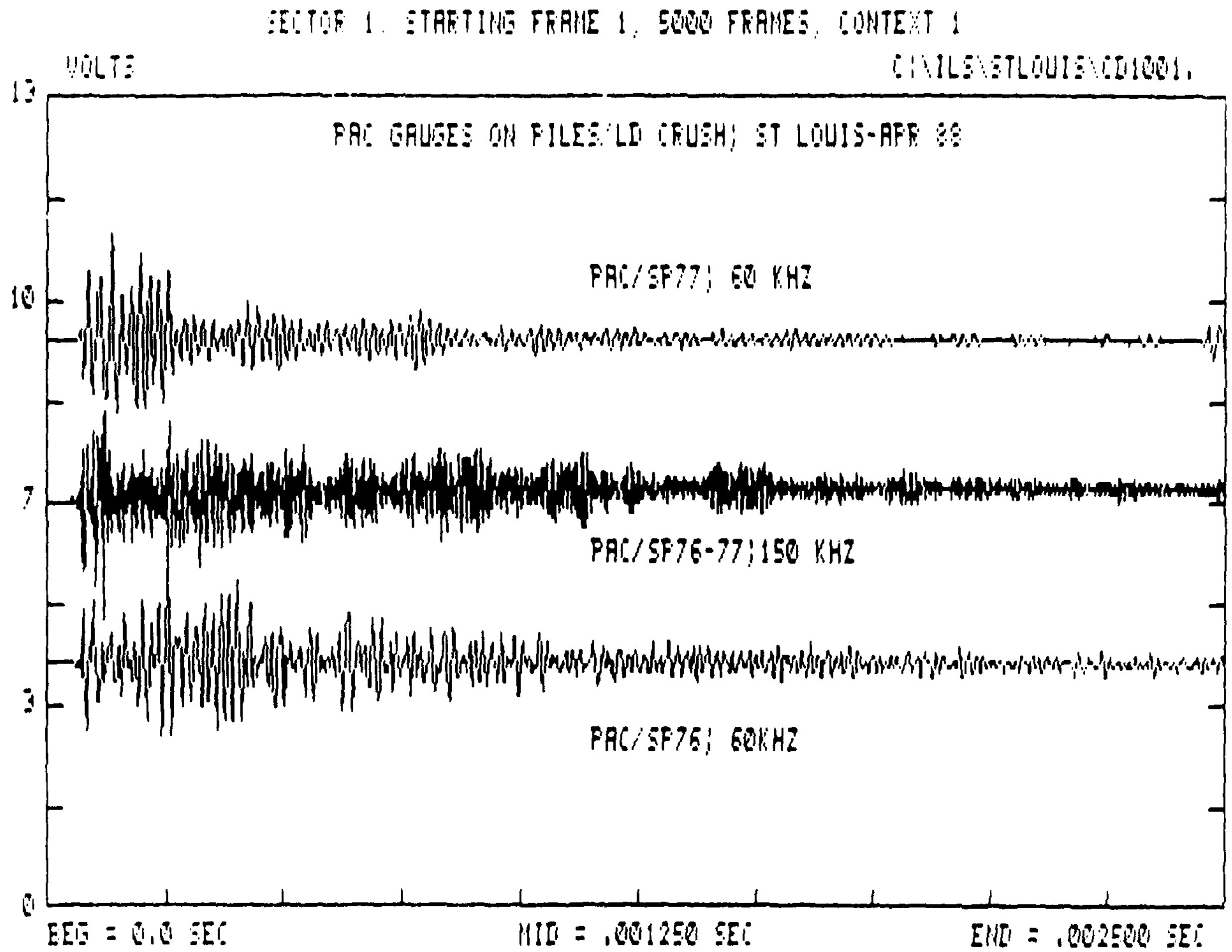


Fig. 7.76. Waveforms in response to a lead break on sheetpiles SP76, SP76-77, SP77

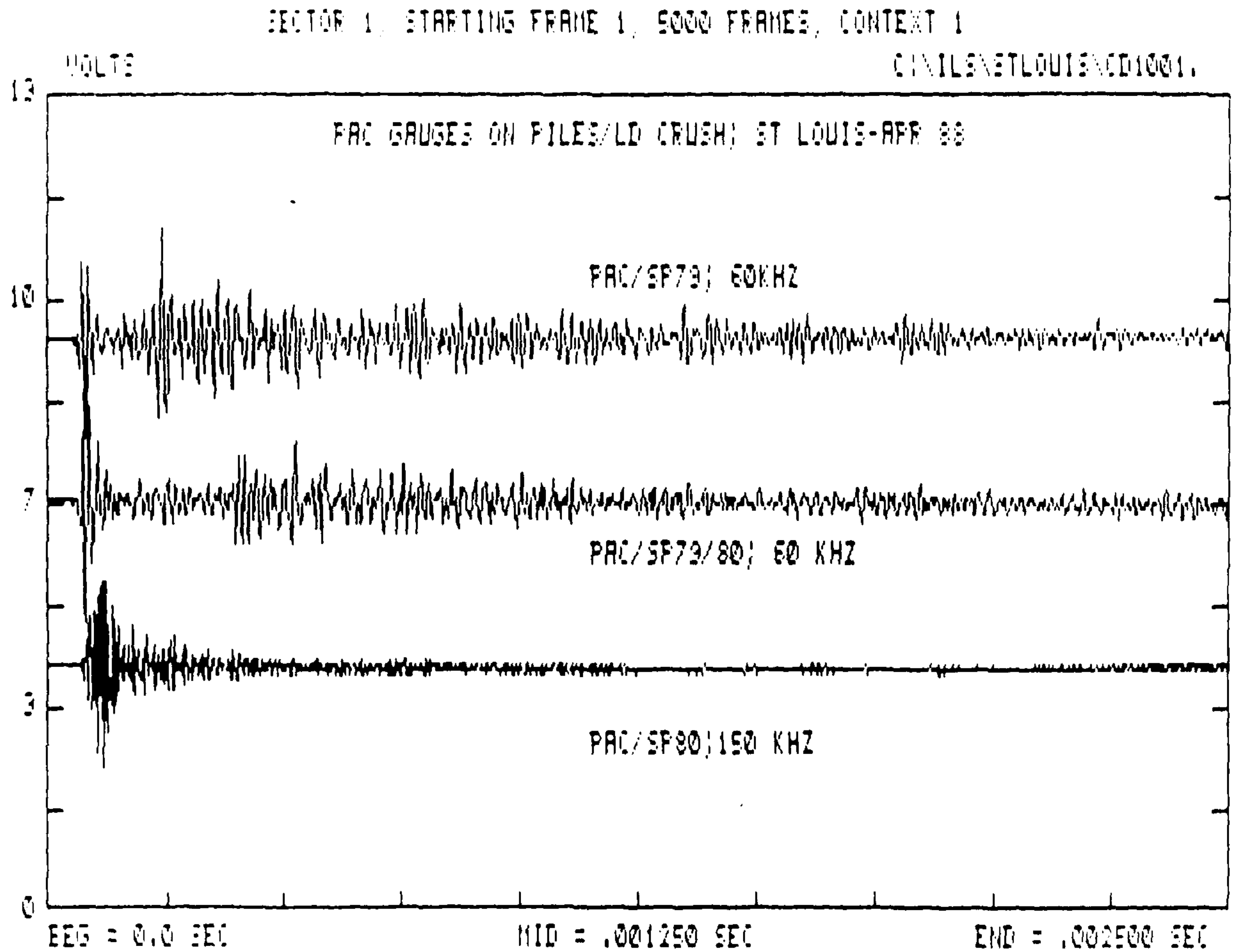


Fig. 7.77. Waveforms in response to a lead break on sheetpiles SP79, SP79-80, SP80

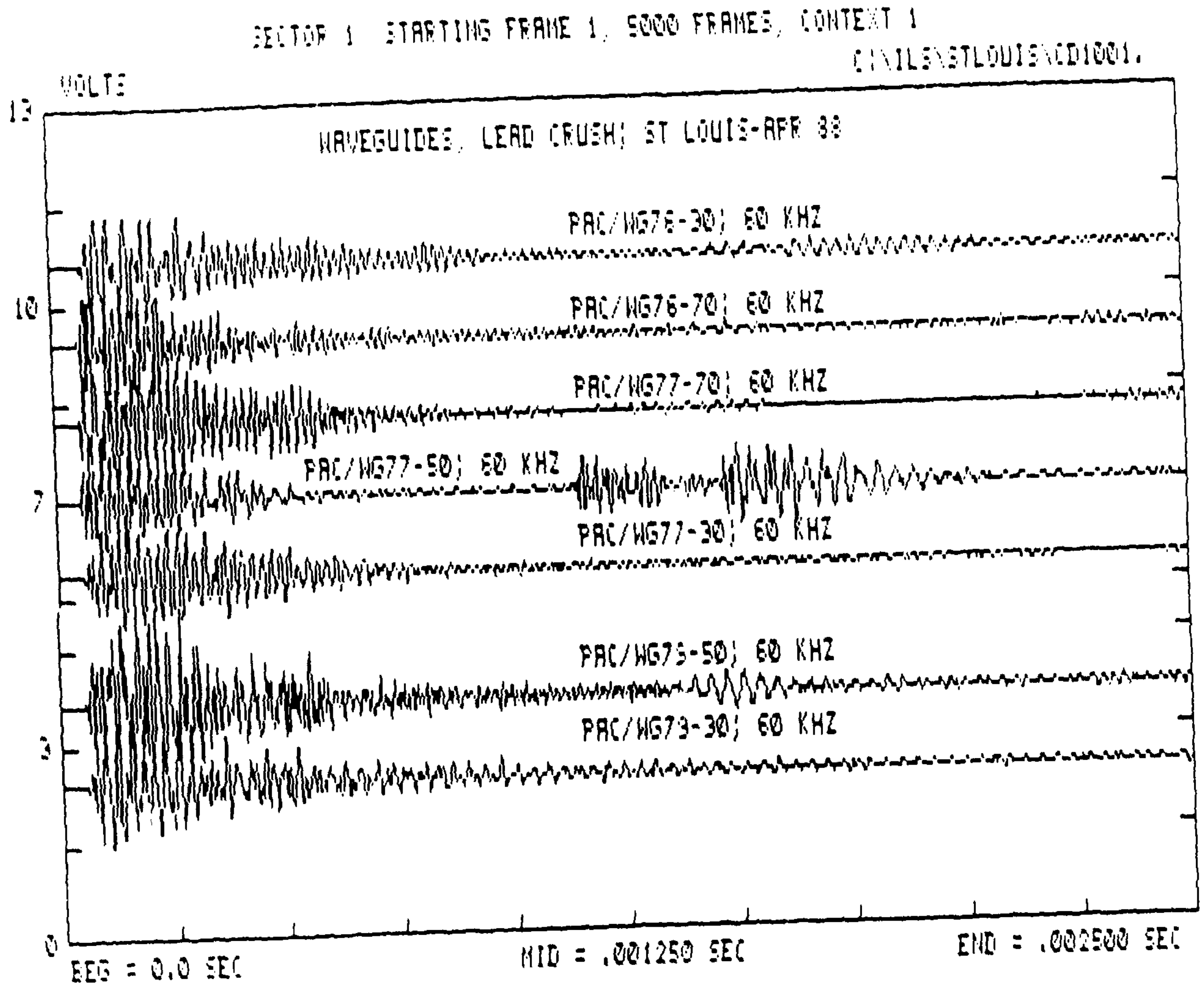


Fig. 7.78. Waveforms in response to a lead break on rod-waveguides (WG)

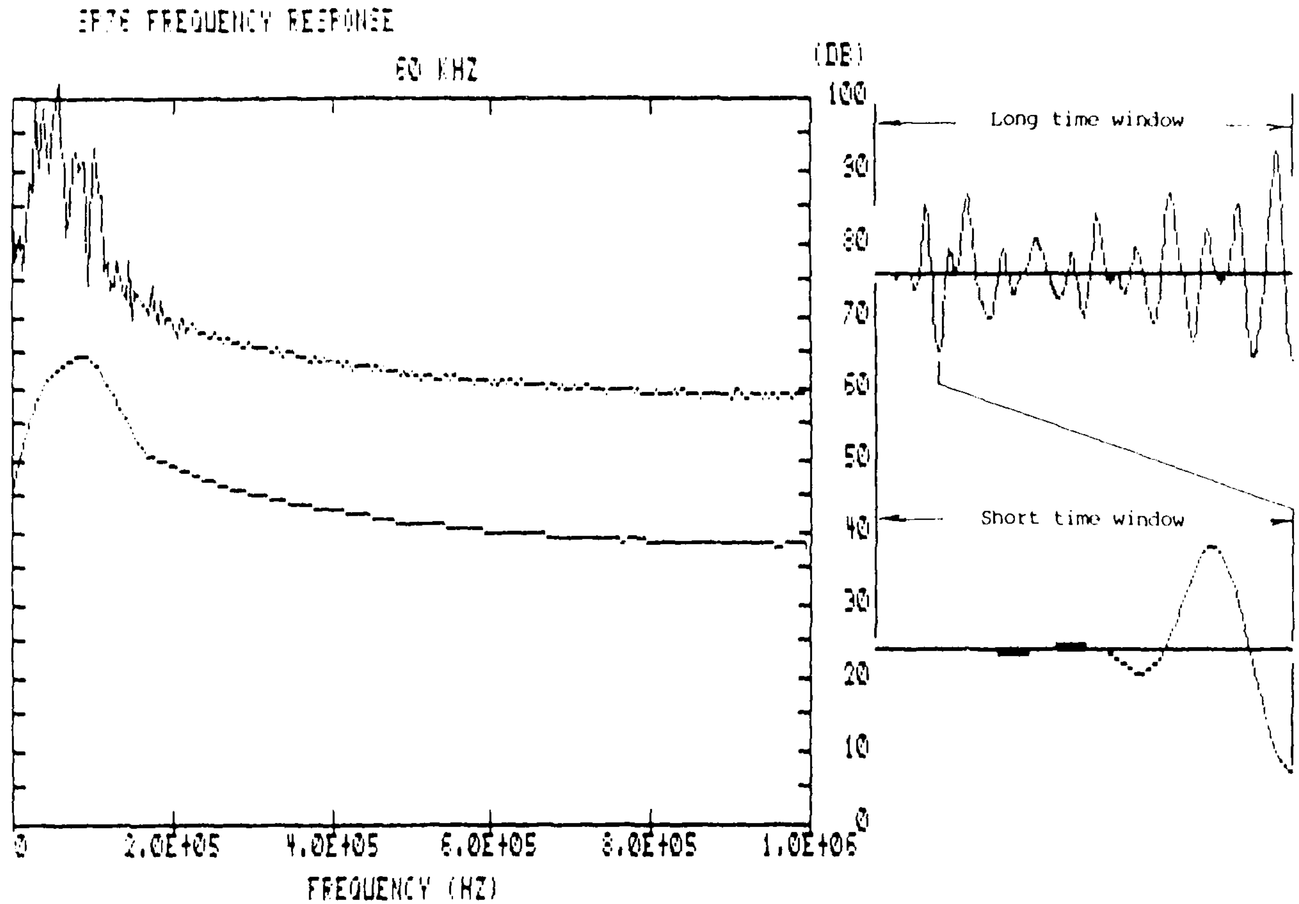


Fig. 7.79. Frequency response to a lead break at SP76 (60kHz)

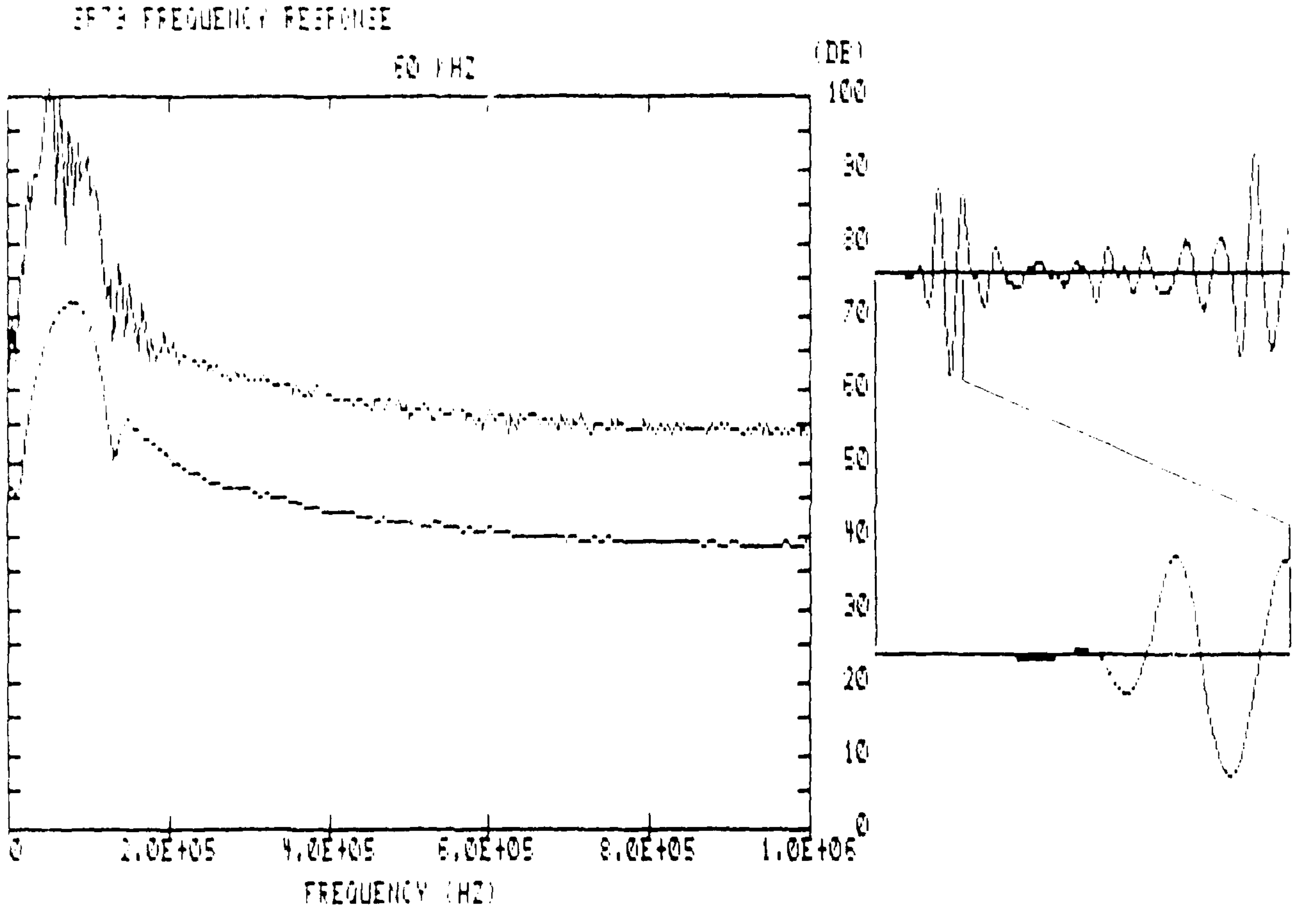


Fig. 7.80. Frequency response to a lead break at SP79 (60kHz)

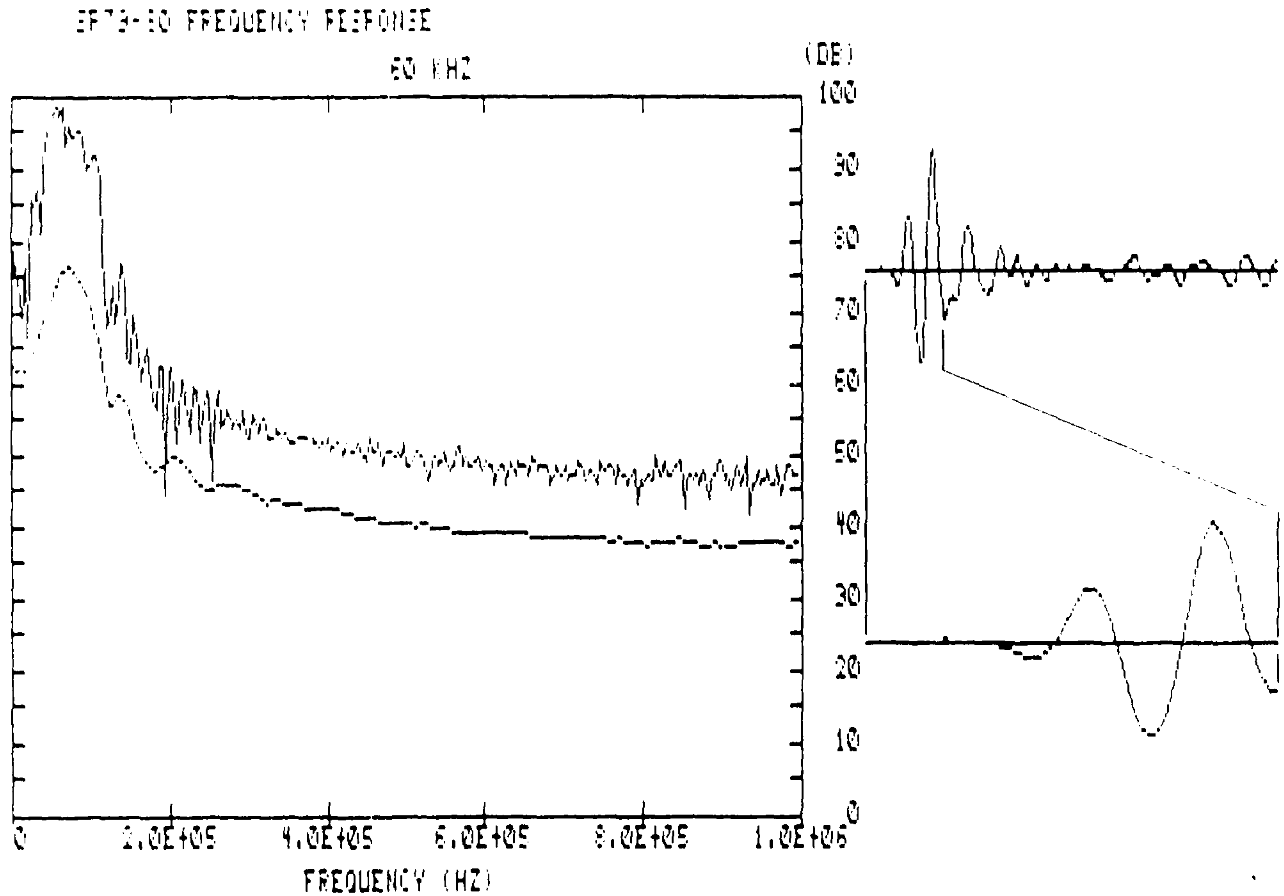


Fig. 7.81. Frequency response to a lead break at SP79-80 (60kHz)

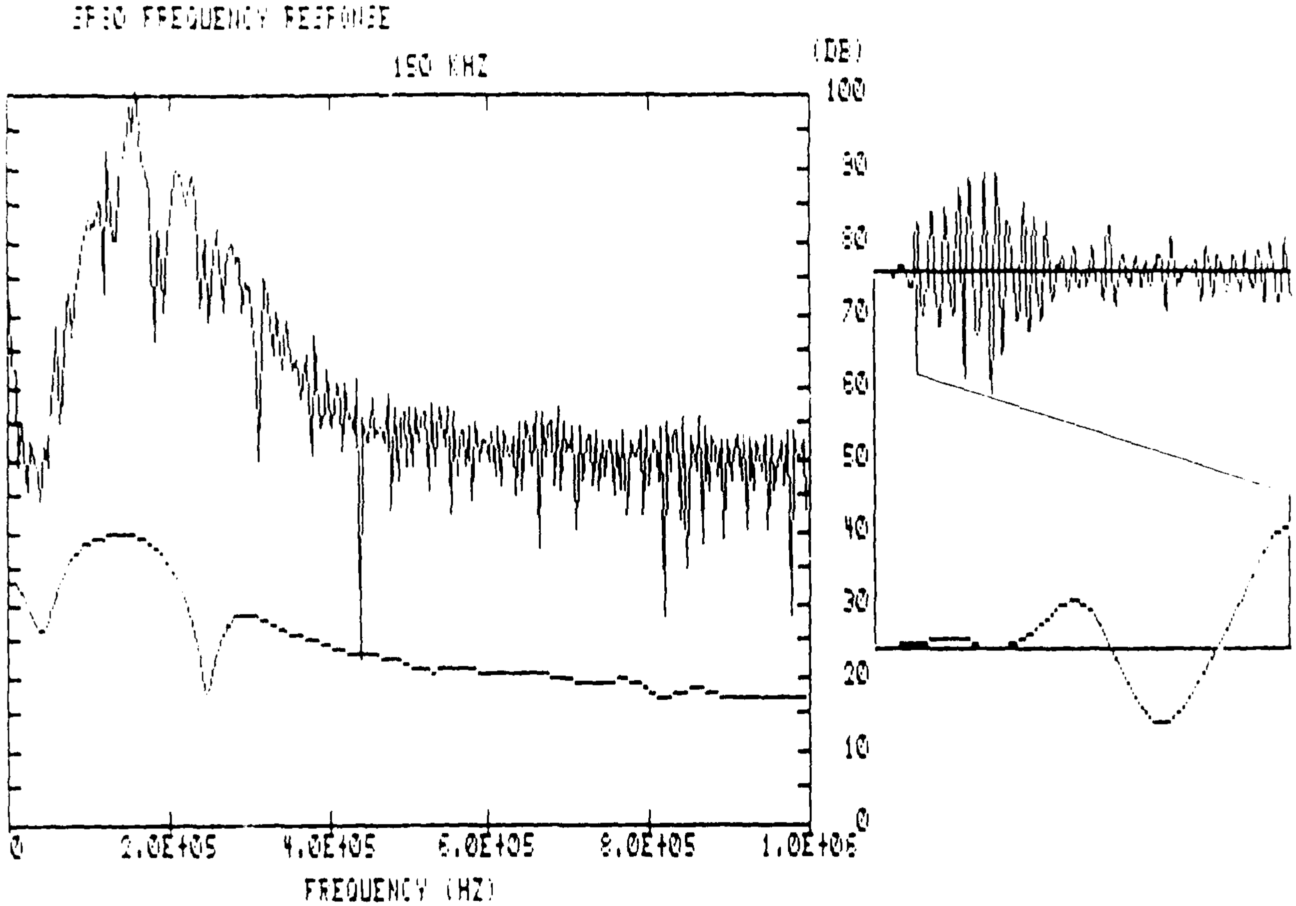


Fig. 7.82. Frequency response to a lead break at SP80 (150kHz)

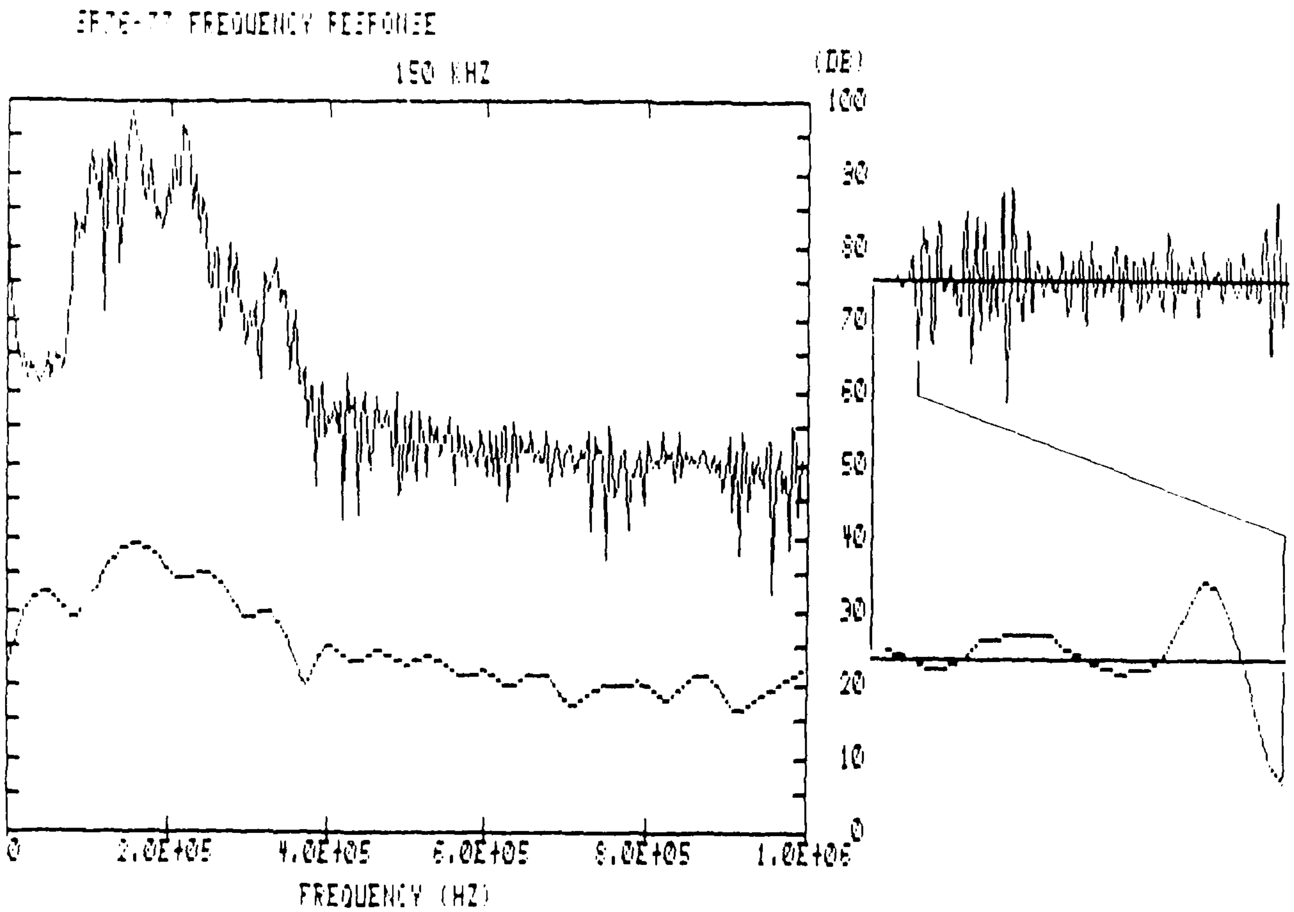


Fig. 7.83. Frequency response to a lead break at SP76-77 (150kHz)

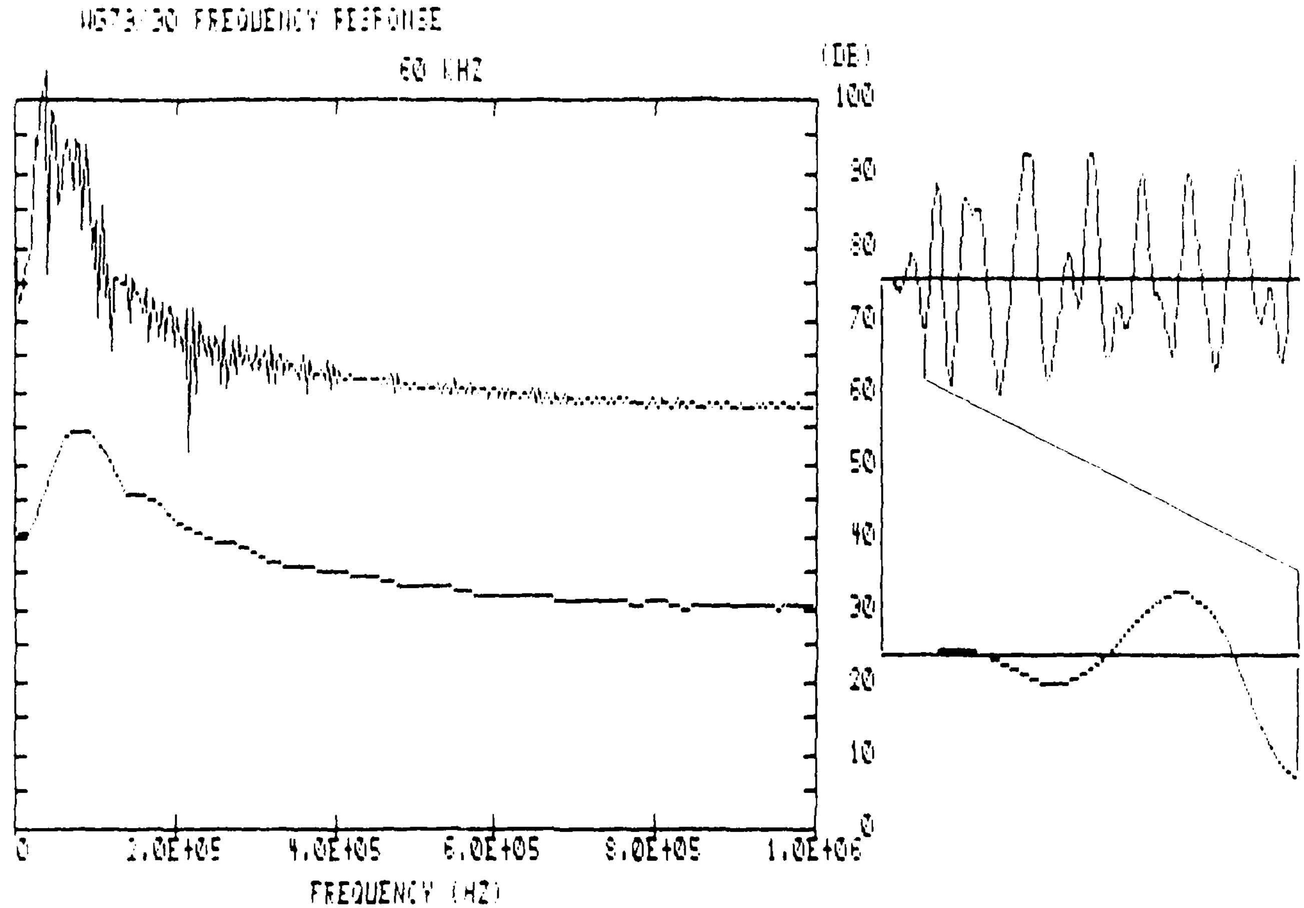


Fig. 7.84. Frequency response to a lead break at WG79/30 (60kHz)

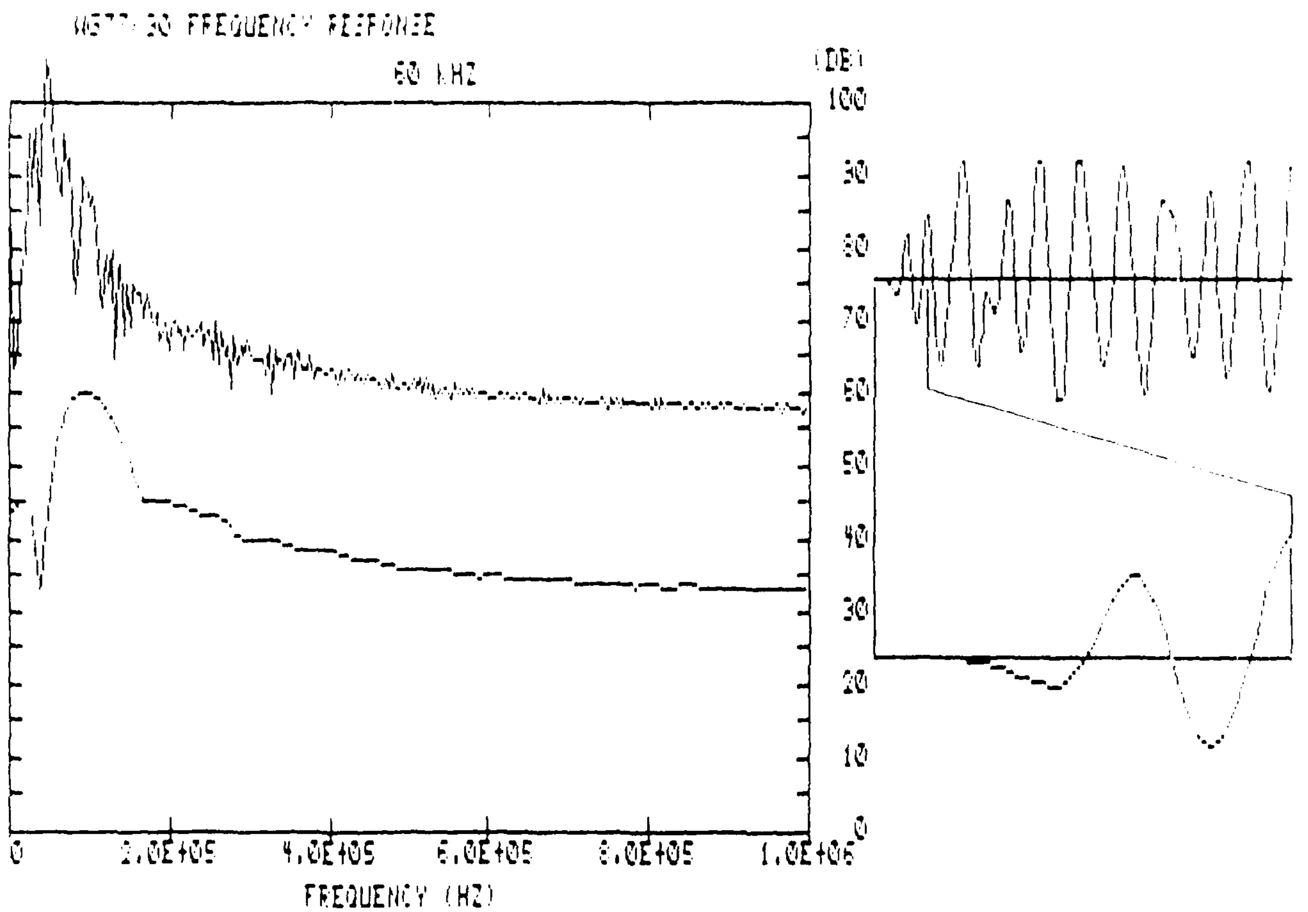


Fig. 7.85. Frequency response to a lead break at WG77/30 (60kHz)

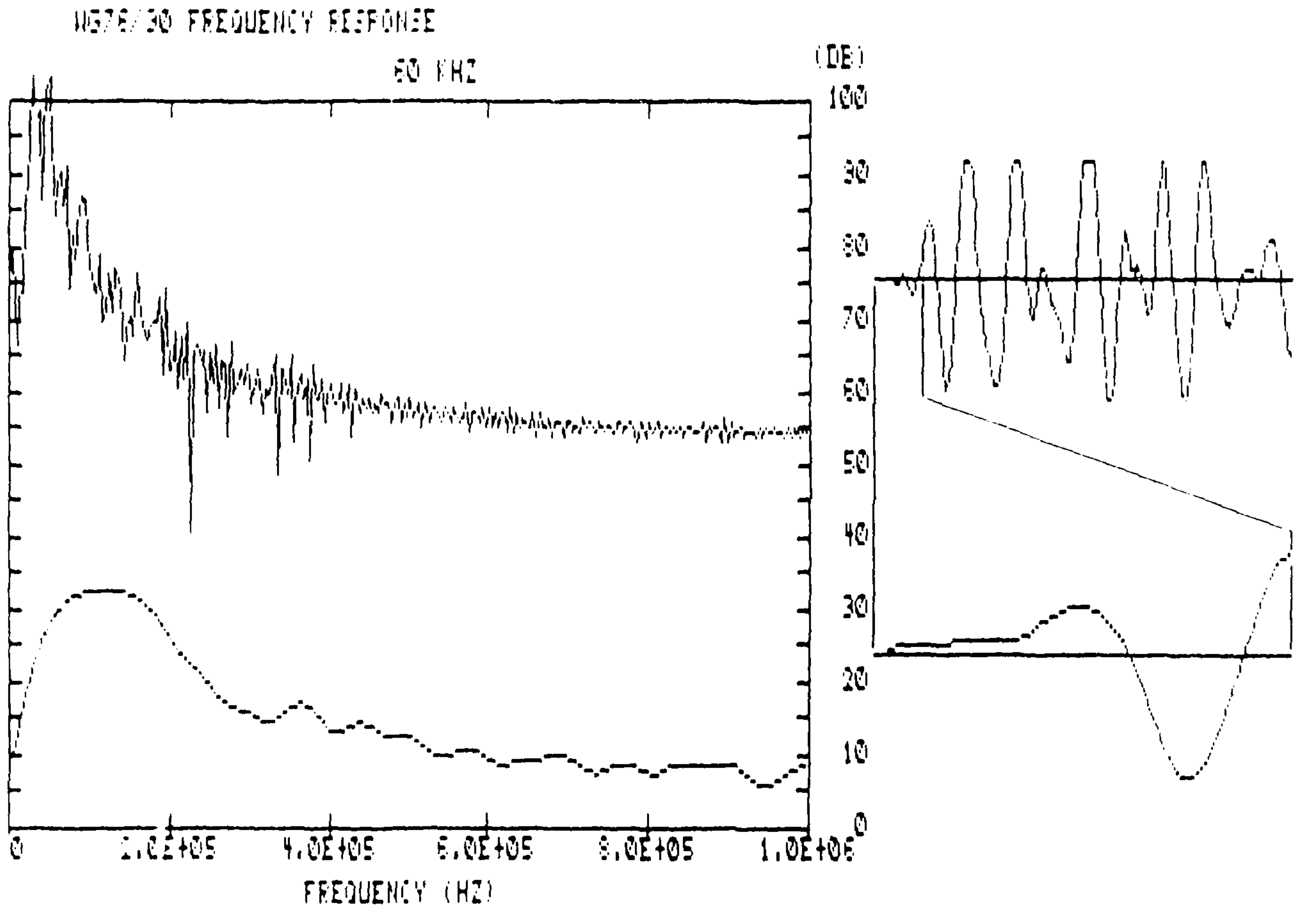


Fig. 7.86. Frequency response to a lead break at WG76/30 (60kHz)

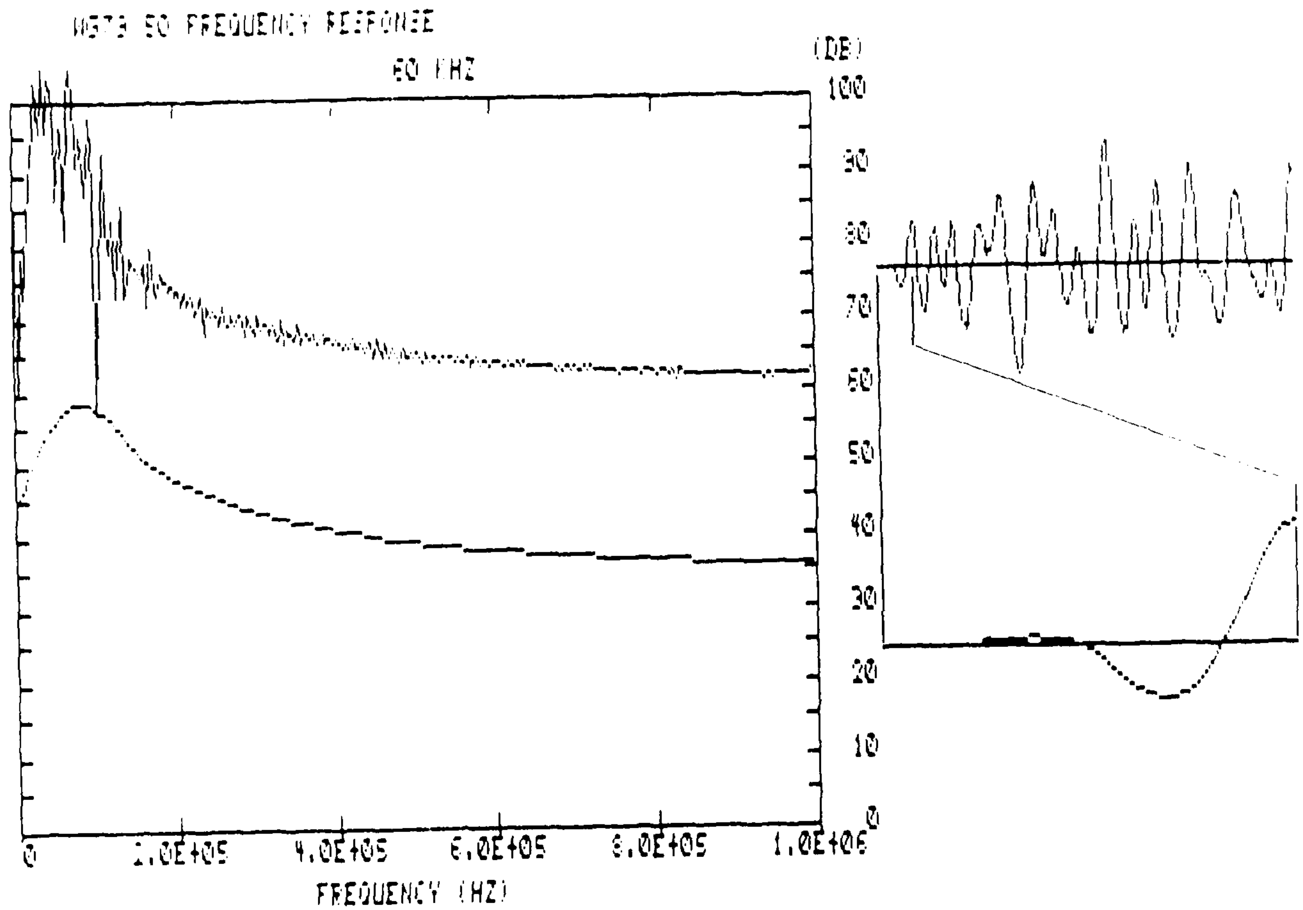


Fig. 7.87. Frequency response to a lead break at WG79/50 (60kHz)

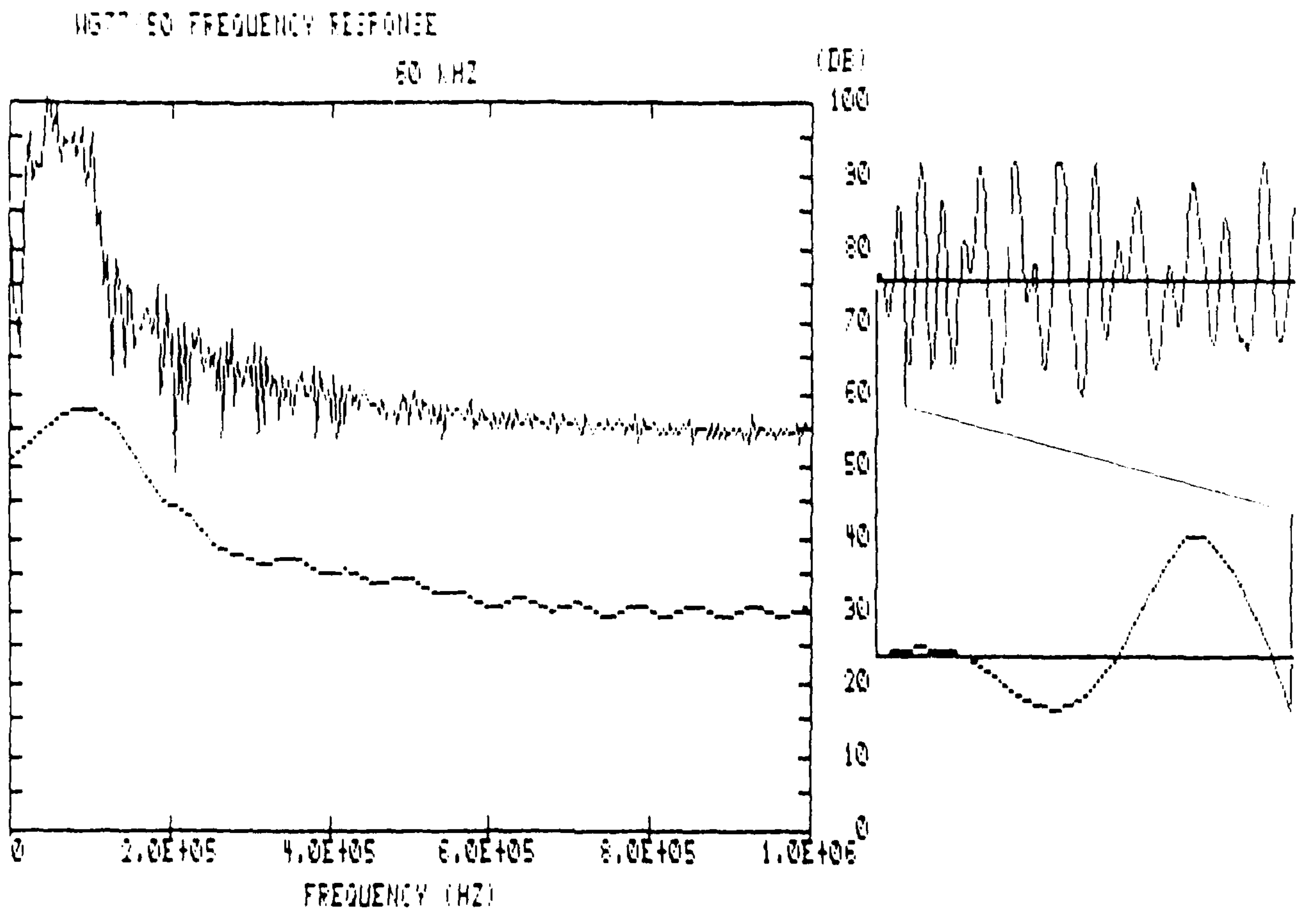


Fig. 7.88. Frequency response to a lead break at WG77/50 (60kHz)

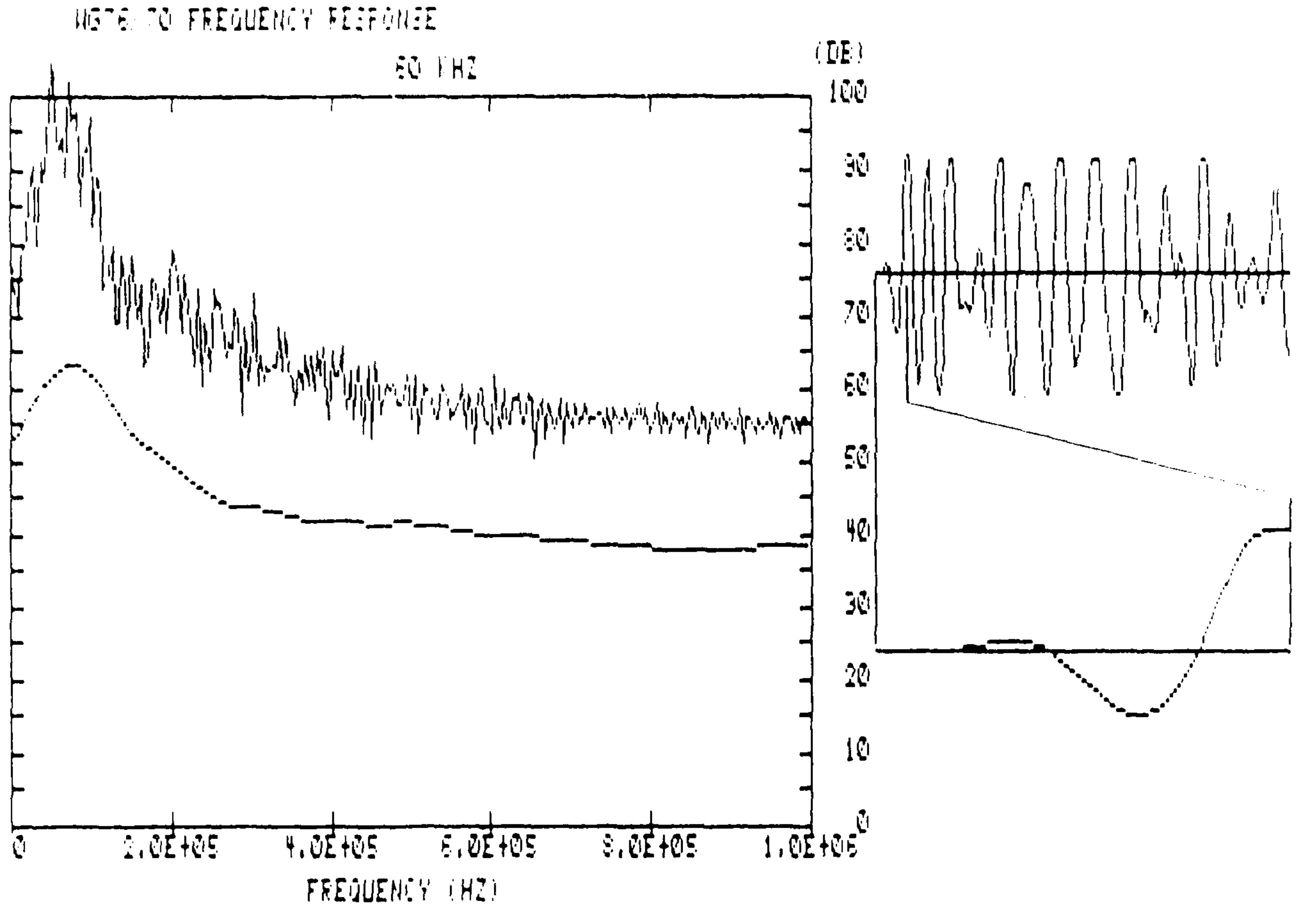


Fig. 7.89. Frequency response to a lead break at WG76/70 (60kHz)

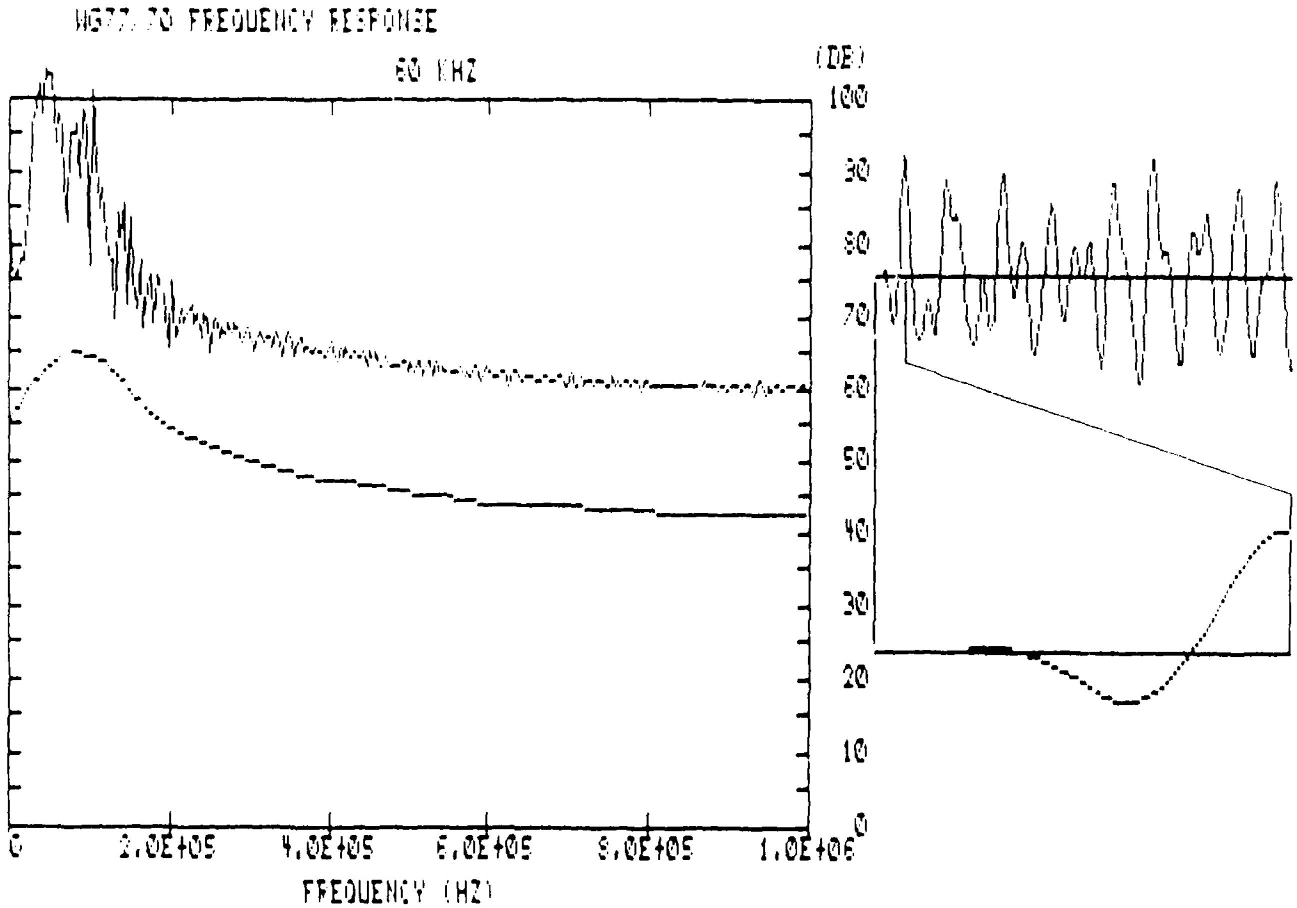


Fig. 7.90. Frequency response to a lead break at WG77/70 (60kHz)

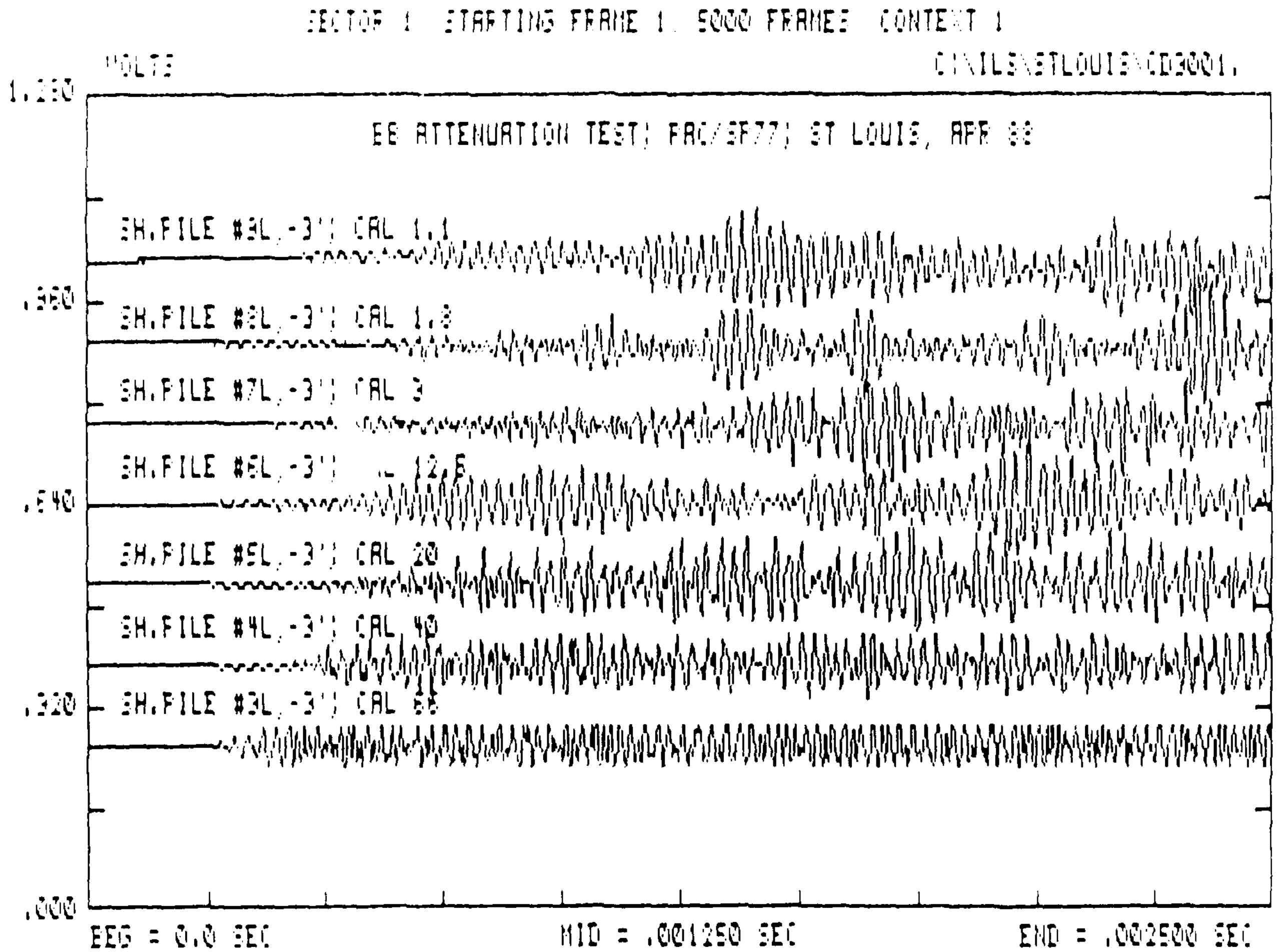


Fig. 7.91. Summary of waveforms from attenuation test at SP77

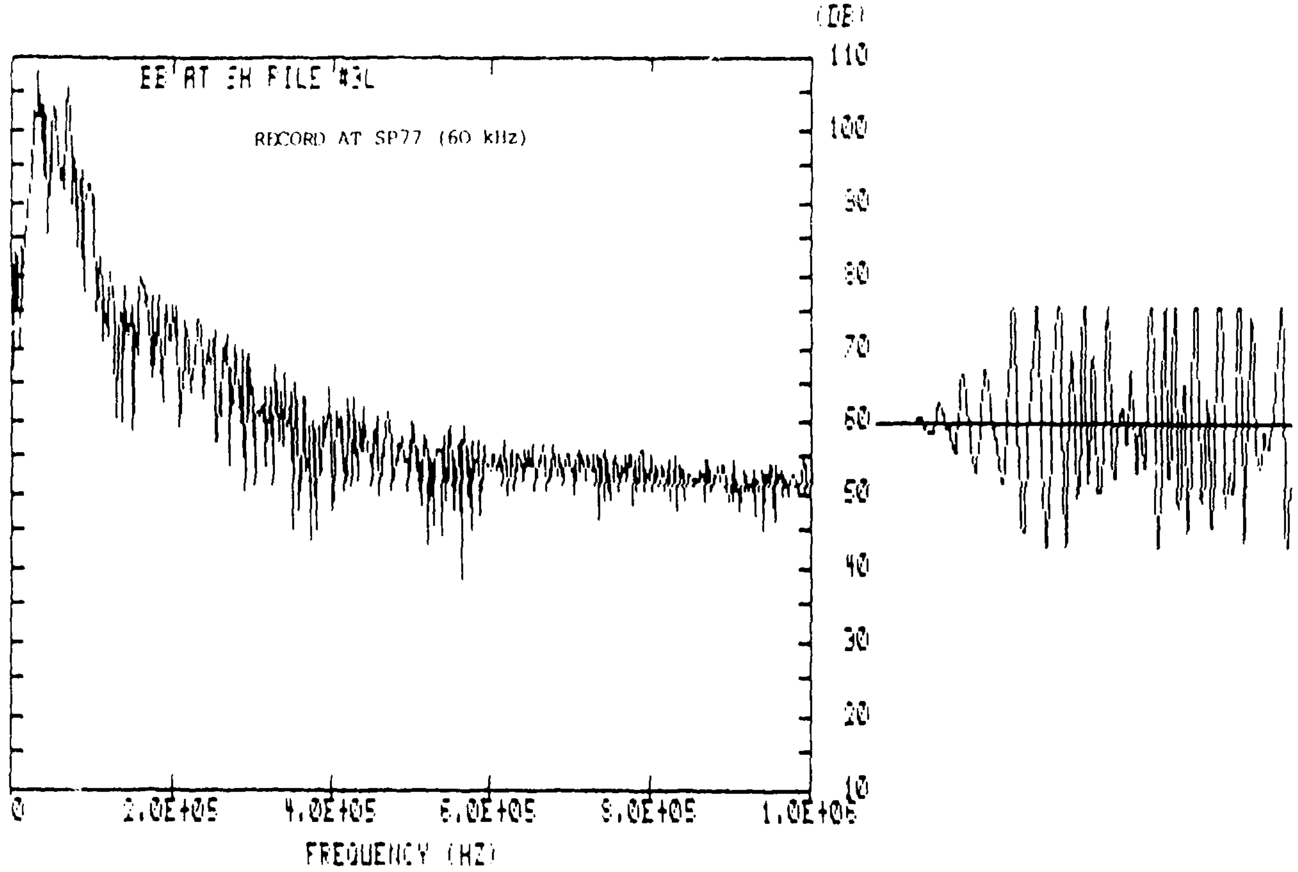


Fig. 7.92. Frequency response at SP77 to a shot at sheetpile 31.

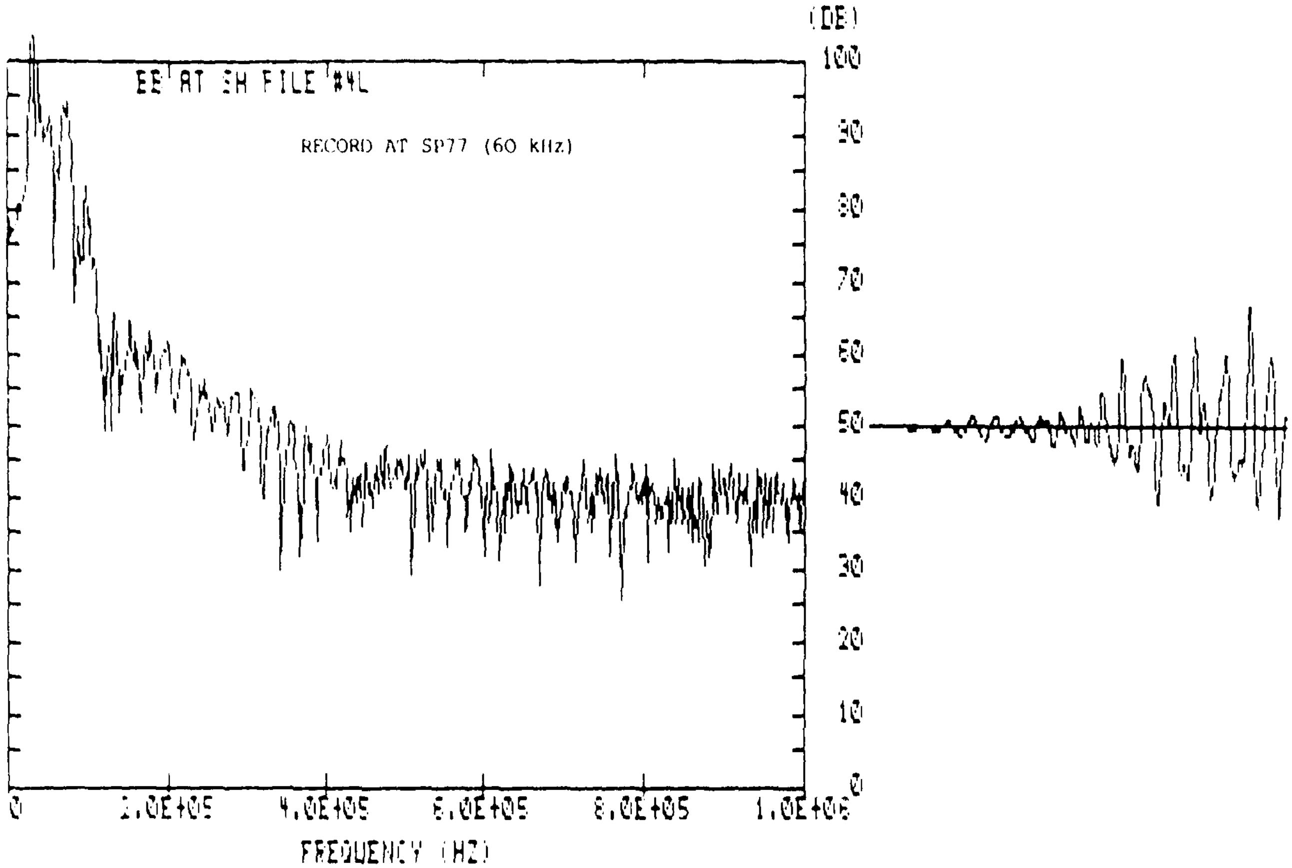


Fig. 7.93. Frequency response at SP77 to a shot at sheetpile 41.

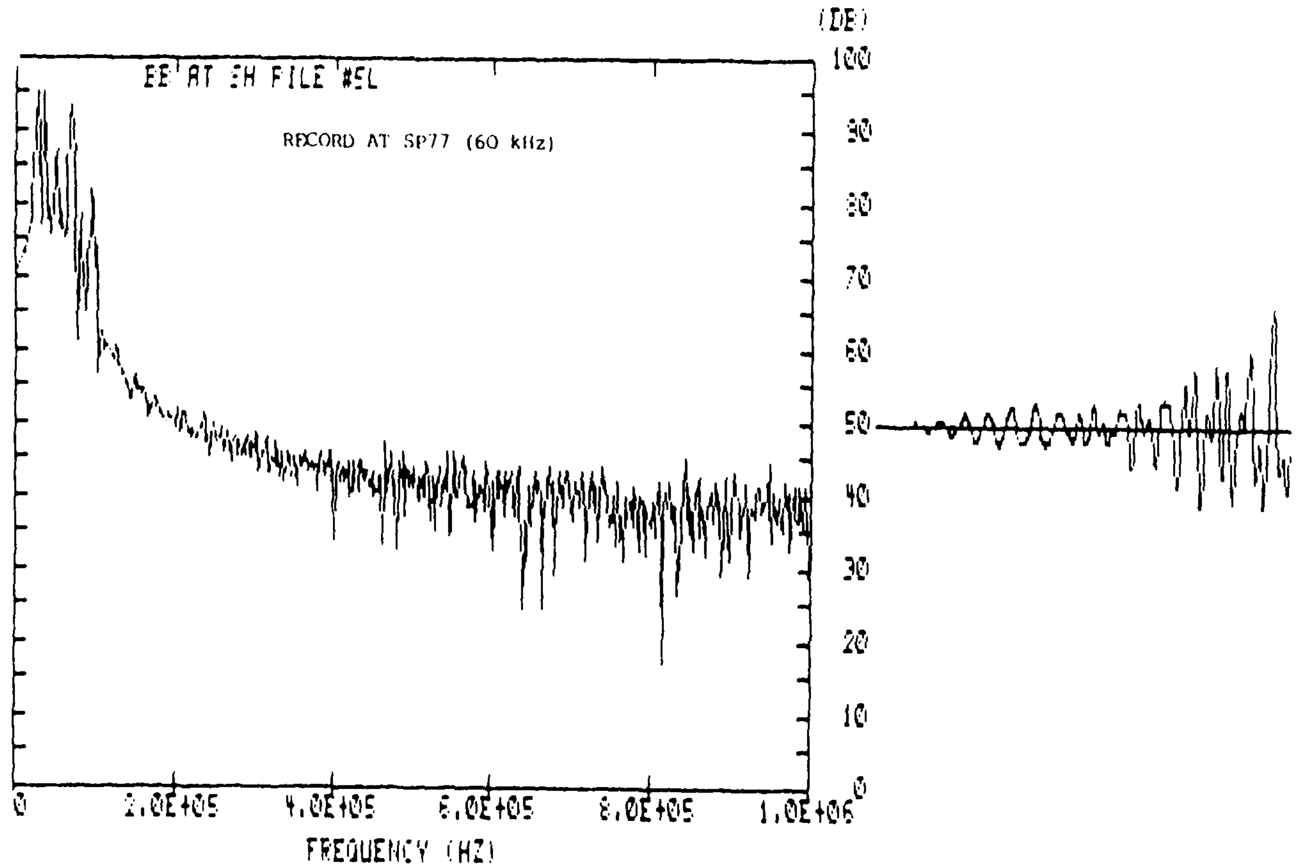


Fig. 7.94. Frequency response at SP77 to a shot at sheetpile 5L.

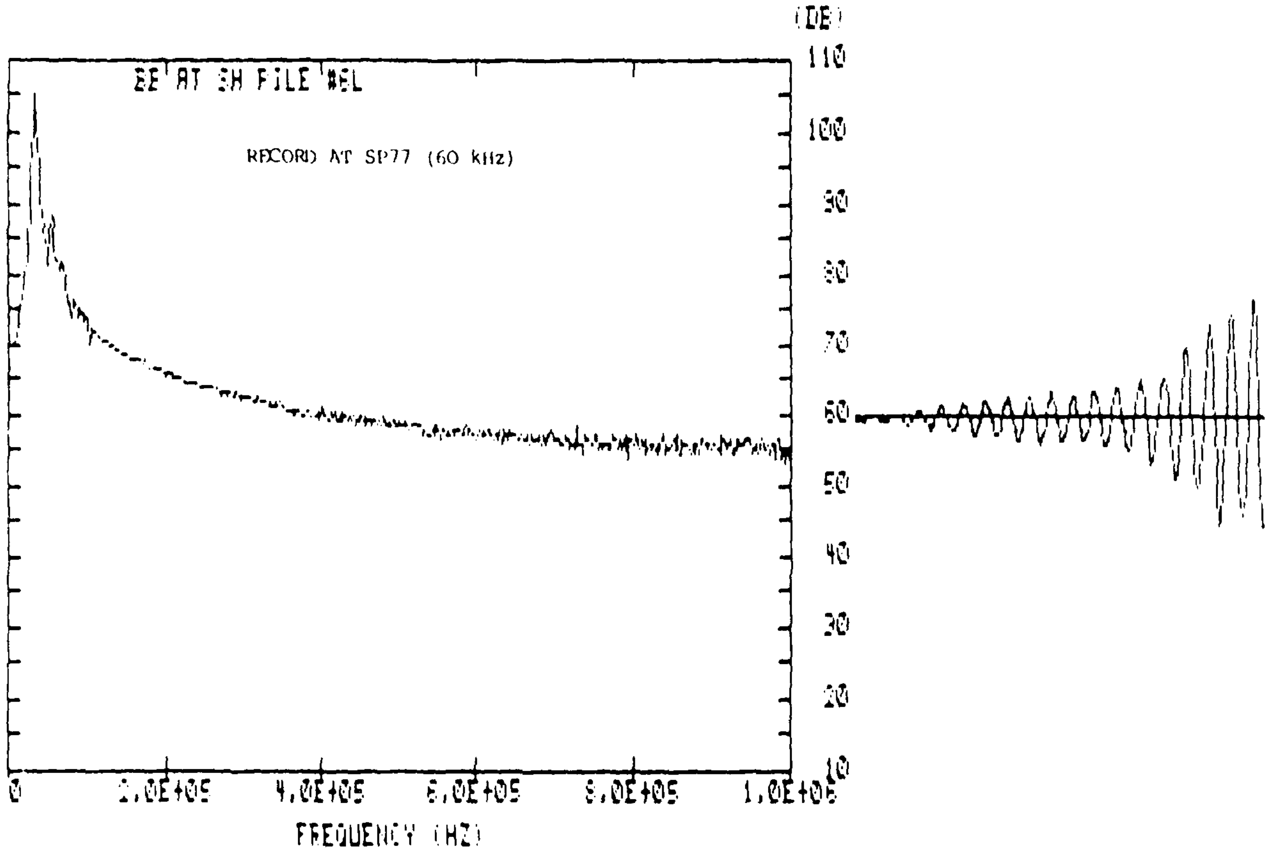


Fig. 7.95. Frequency response at SP77 to a shot at sheetpile 61.

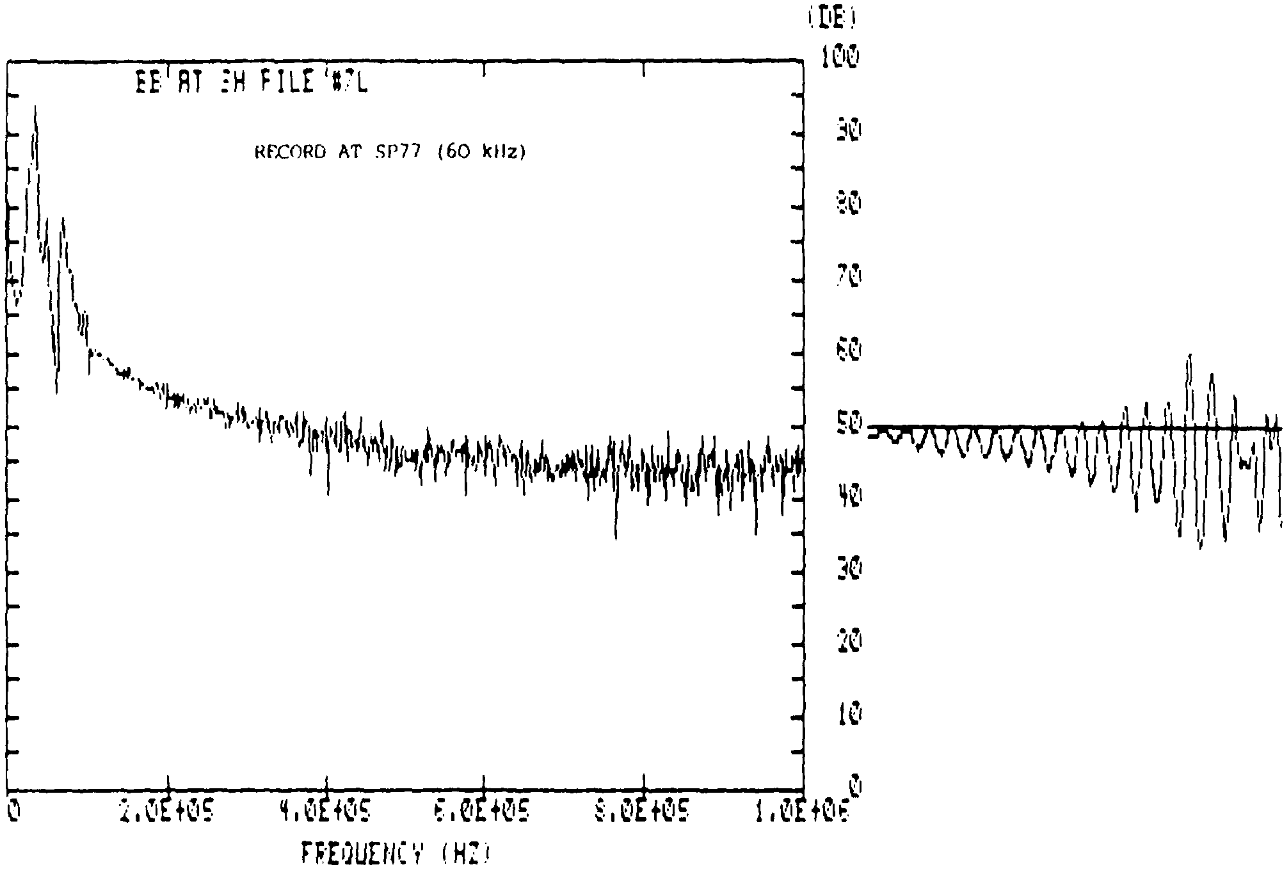


Fig. 7.96. Frequency response at SP77 to a shot at sheetpile 7L.

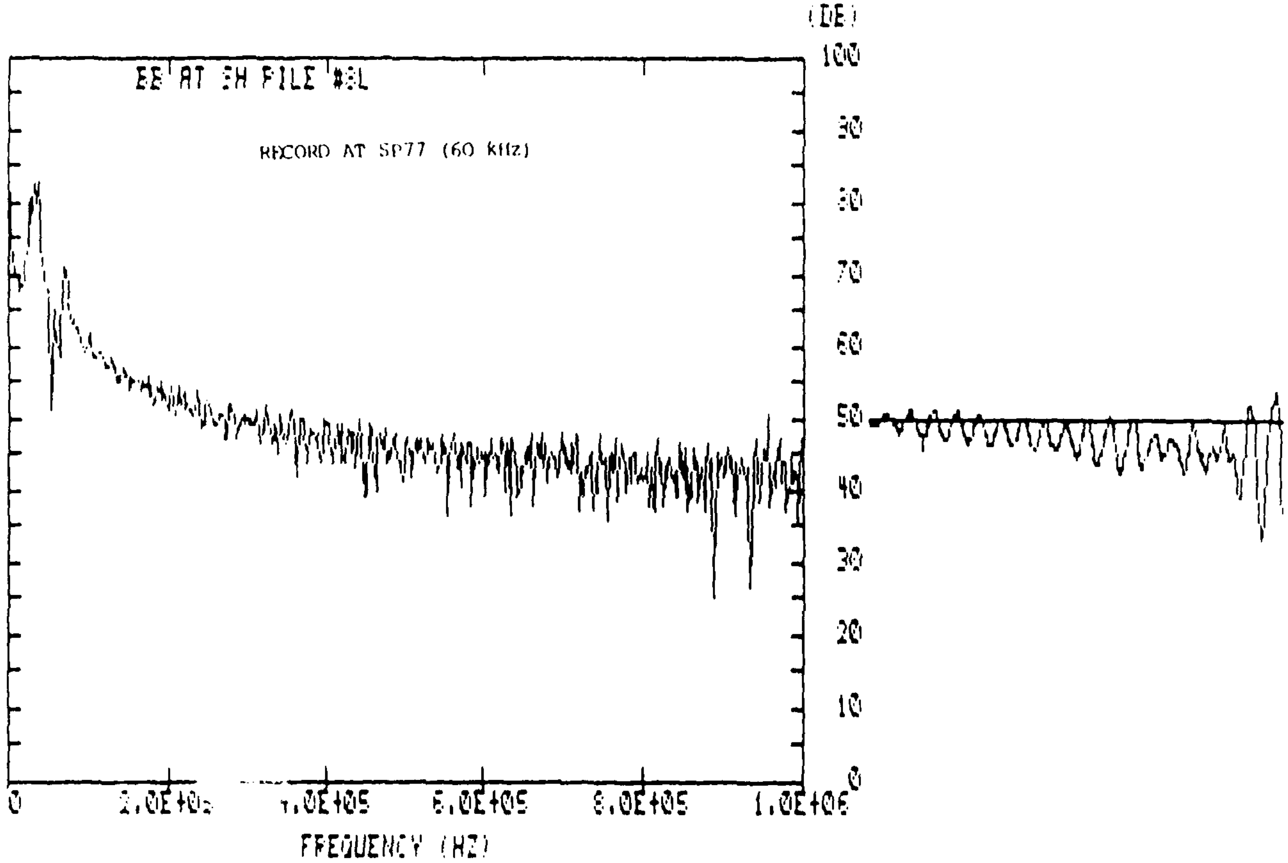


Fig. 7.97. Frequency response at SP77 to a shot at sheetpile 8L

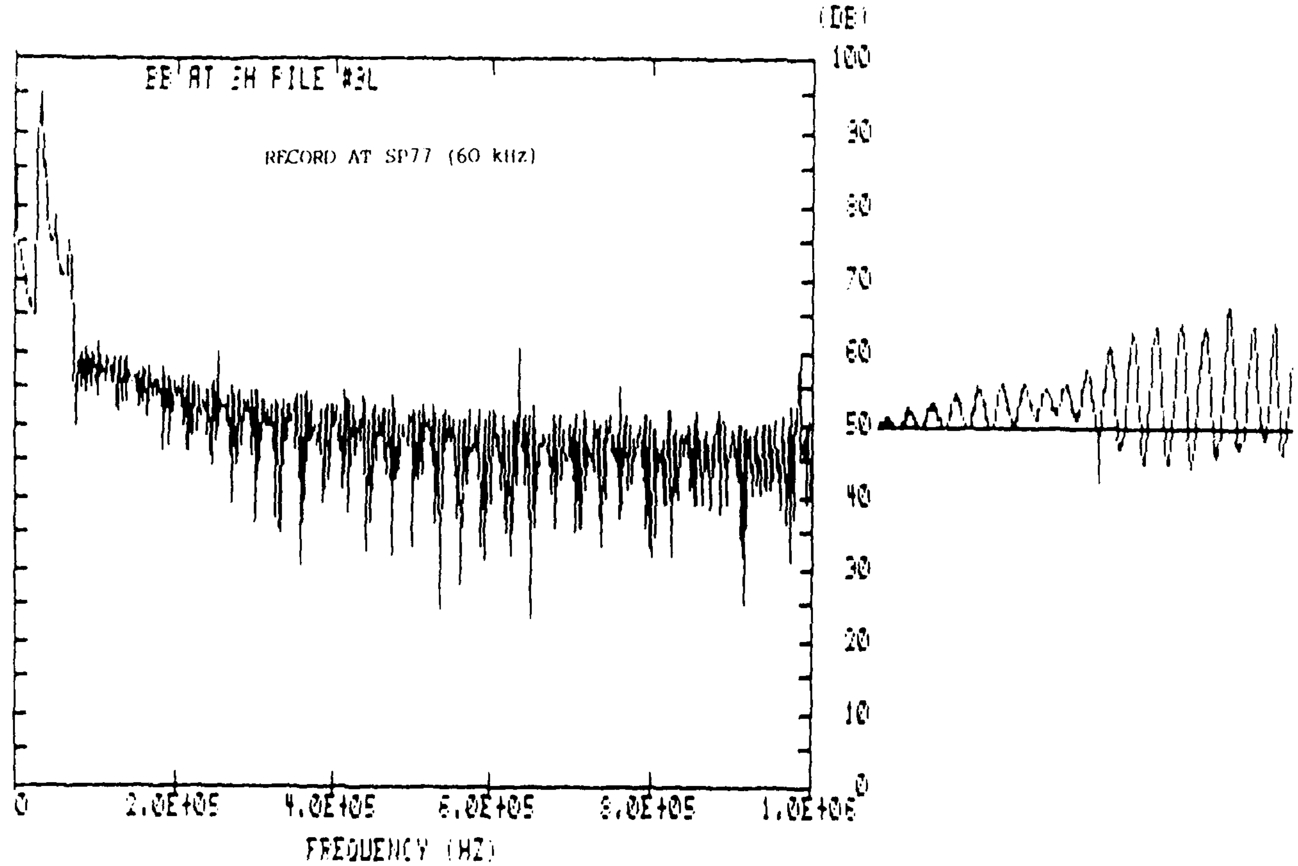


Fig. 7.98. Frequency response at SP77 to a shot at sheetpile 91.

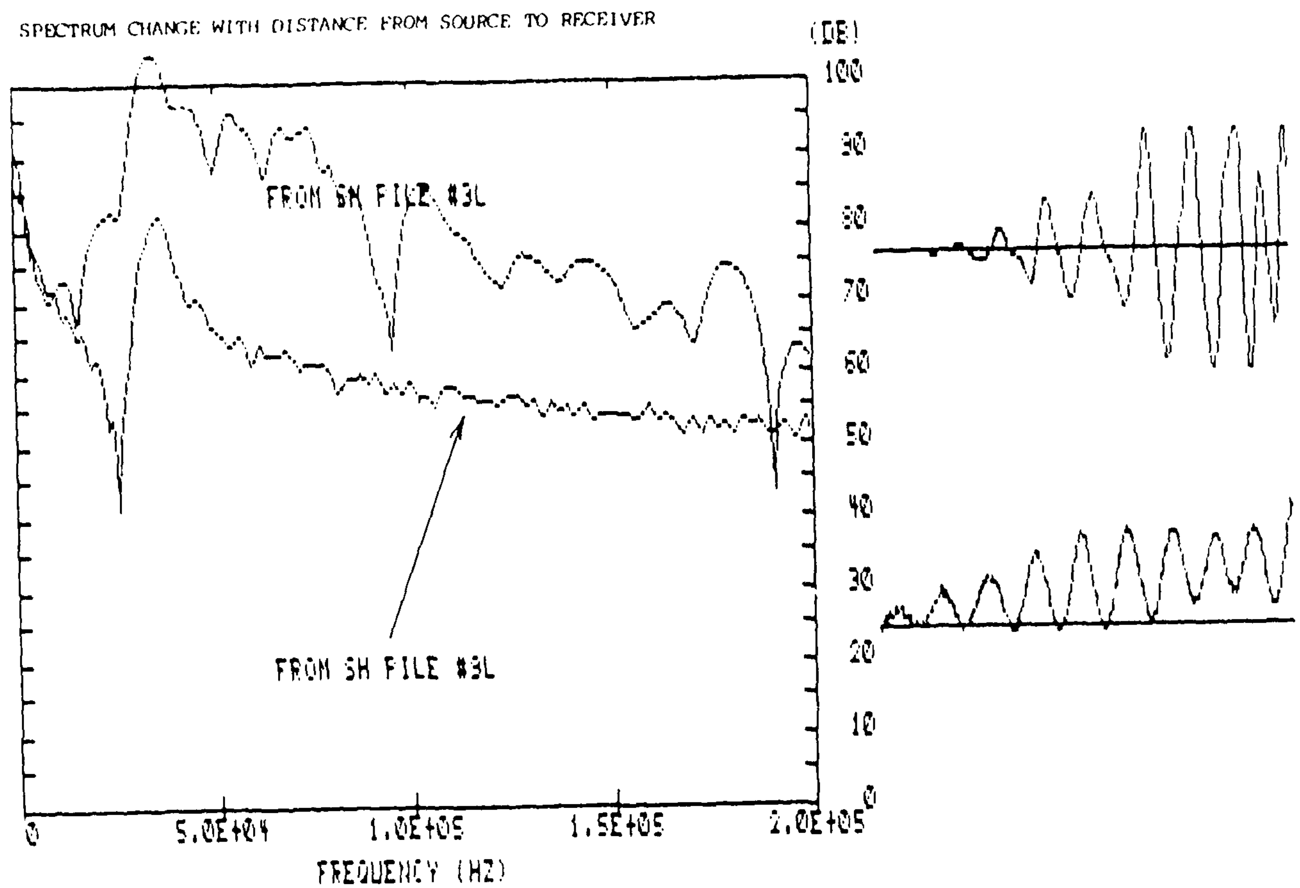


Fig. 7.99. Comparison of frequency response at SP77 as generated ay sheetpiles 3L and 9L

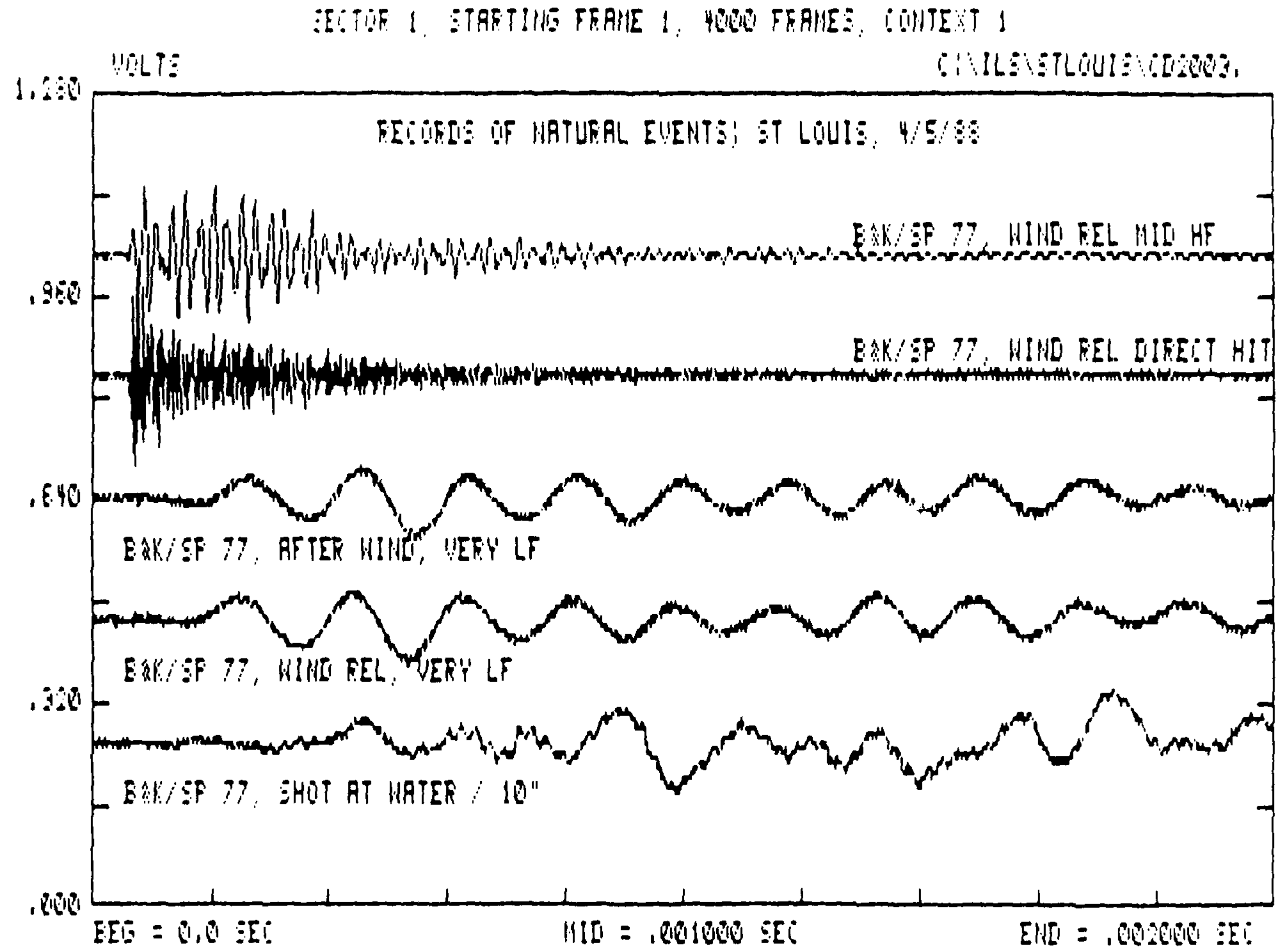


Fig. 7.100. Waveforms of natural events and a shot at water as recorded at SP77 by B&K accelerometer

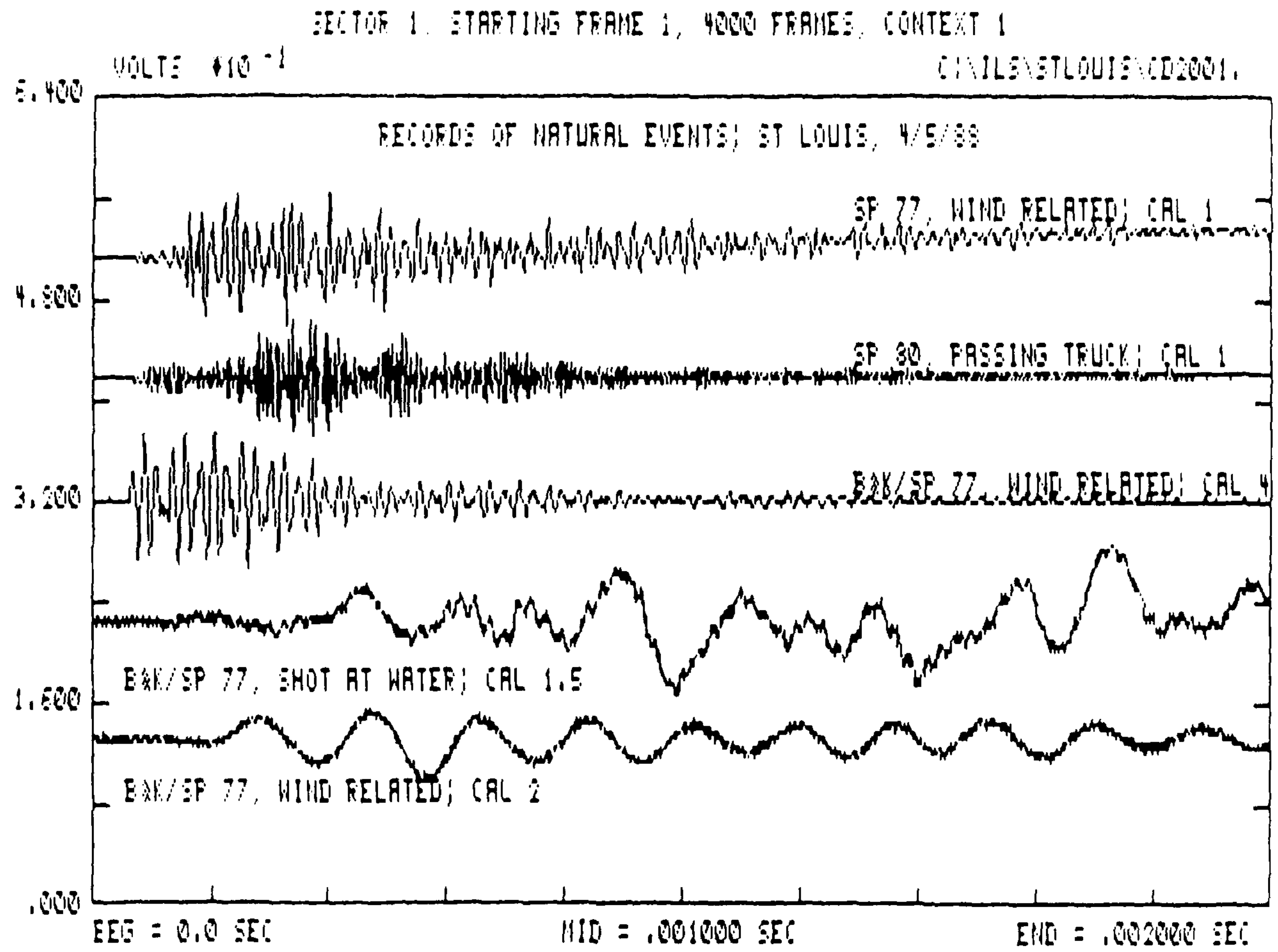


Fig. 7.101. Waveforms of natural events, shot, and passing truck as recorded by PAC and B&K accelerometer.

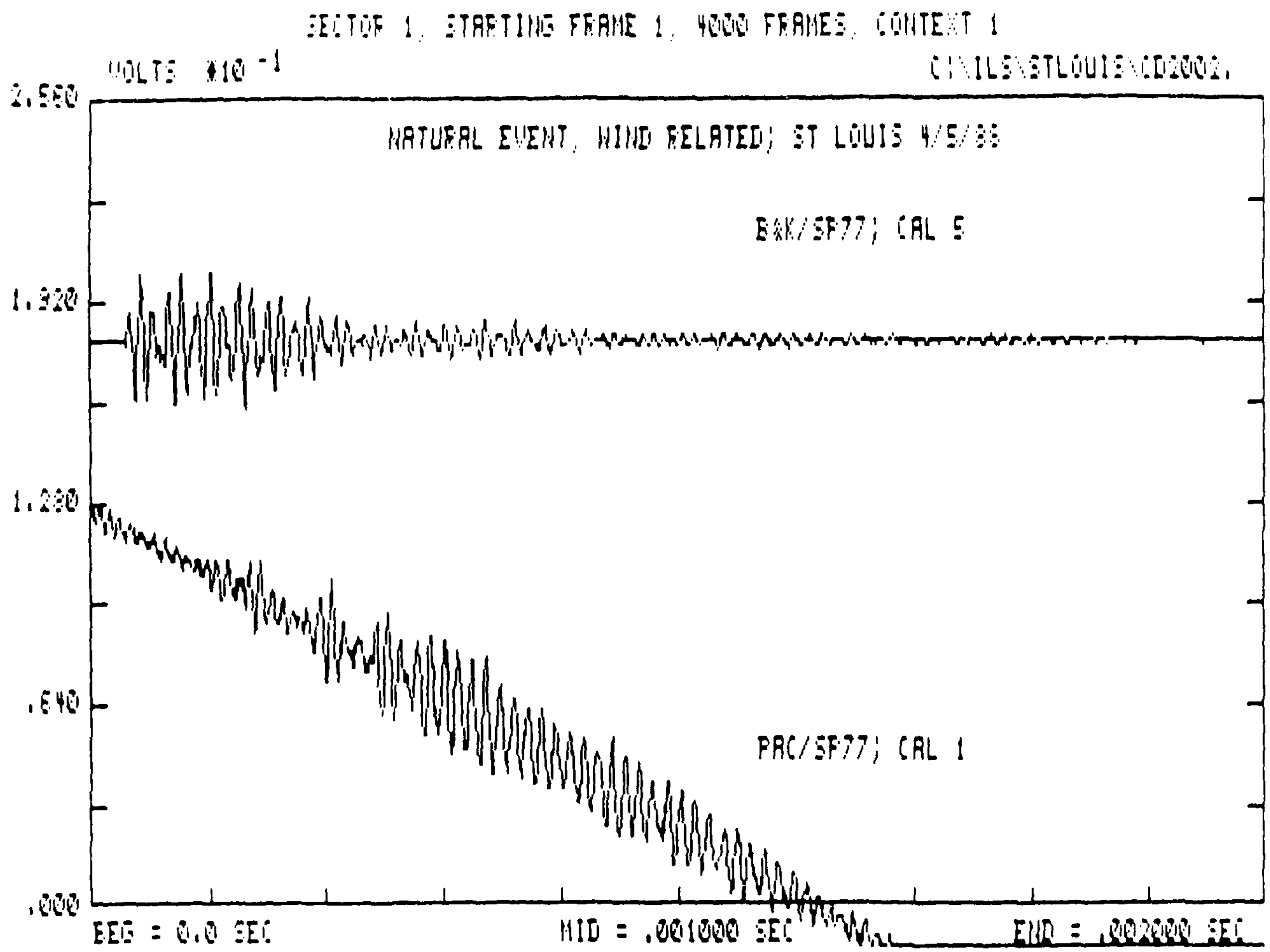


Fig. 7.102. Waveforms of natural event of moderate frequency as recorded simultaneously at SP77 by B&K and PAC accelerometers

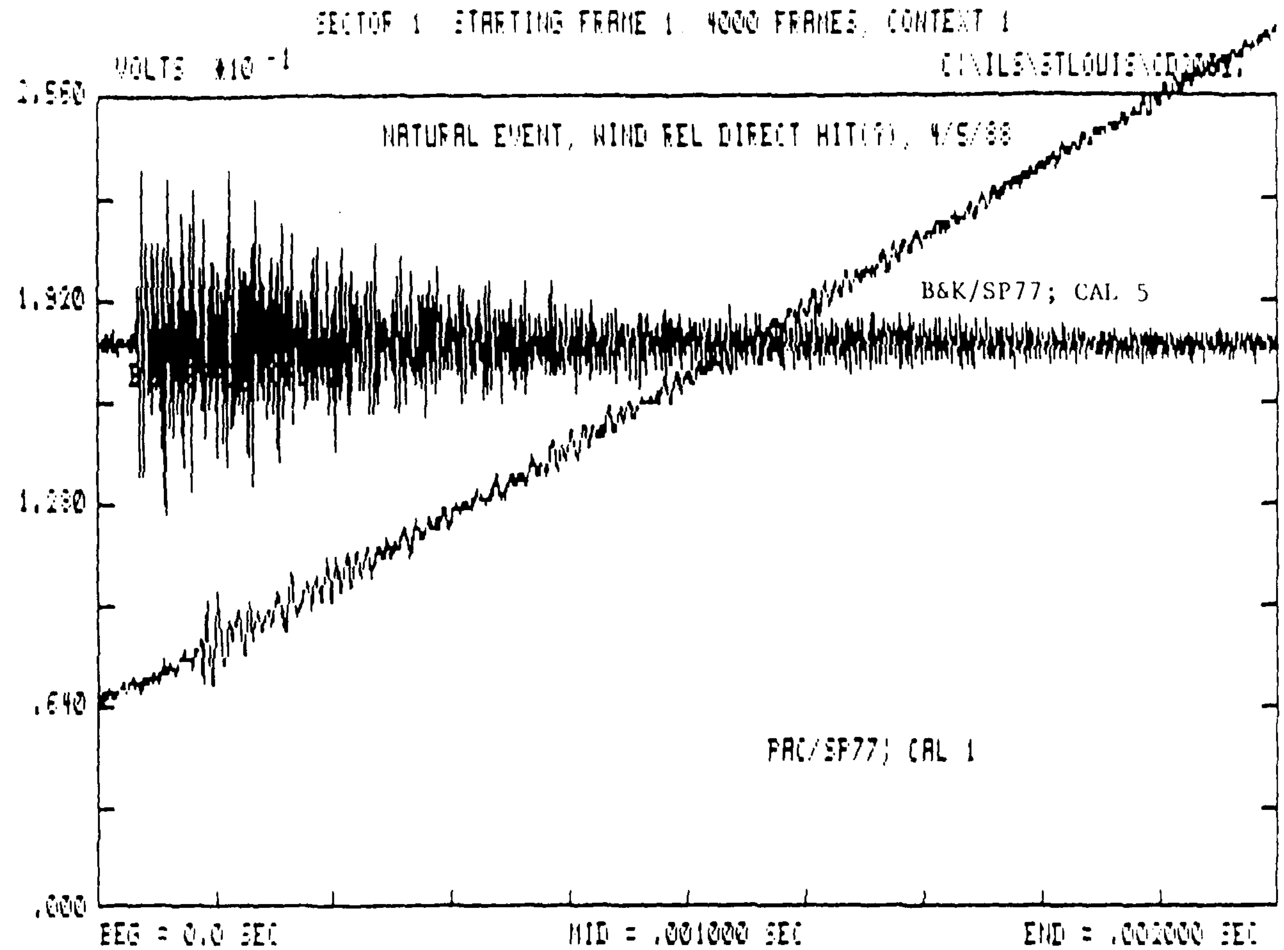


Fig. 7.103. Example 1 of waveforms of high frequency event recorded at SP77 by B&K and PAC accelerometers

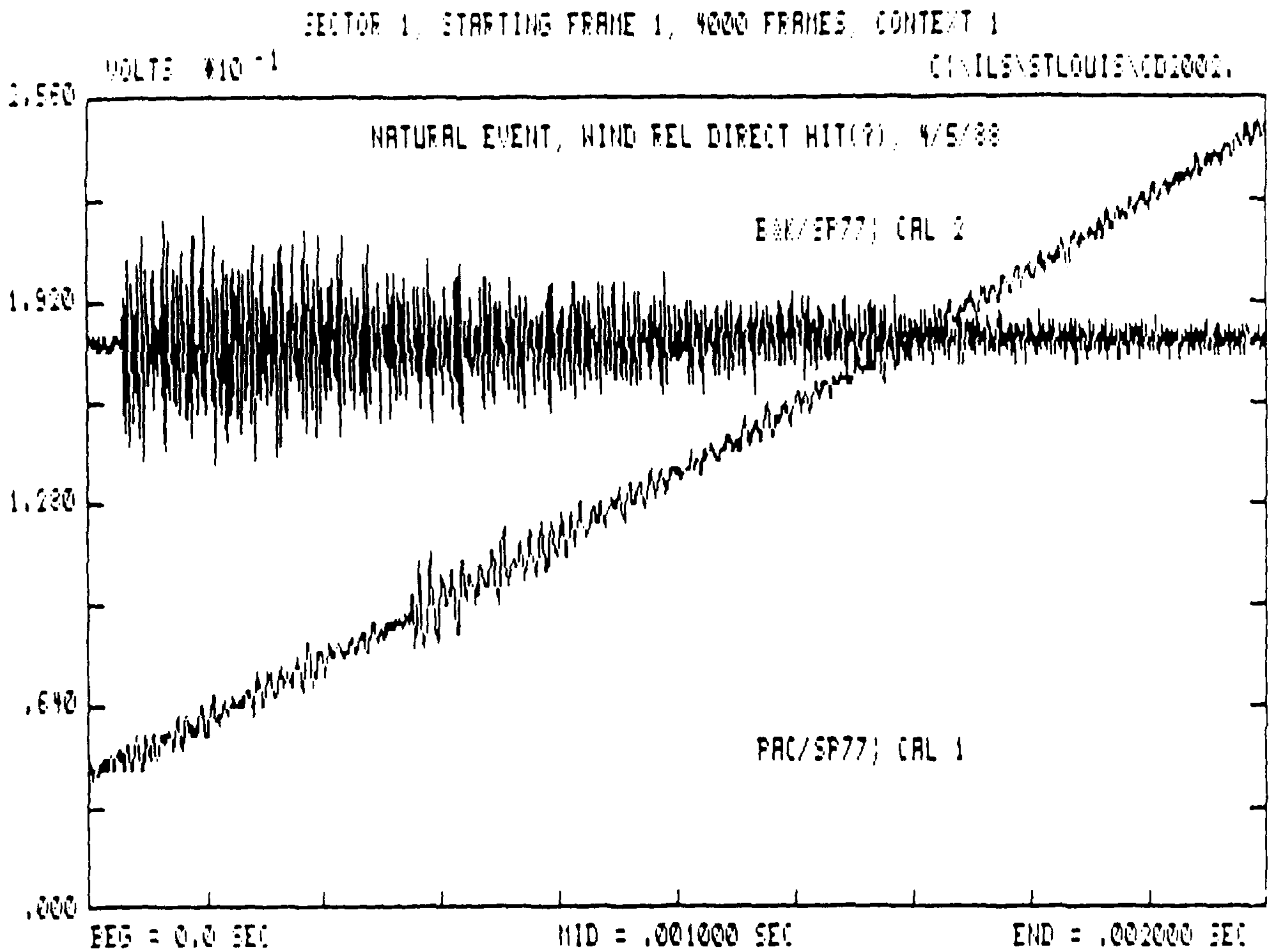


Fig. 7.104. Example 2 of high frequency waveforms at SP77

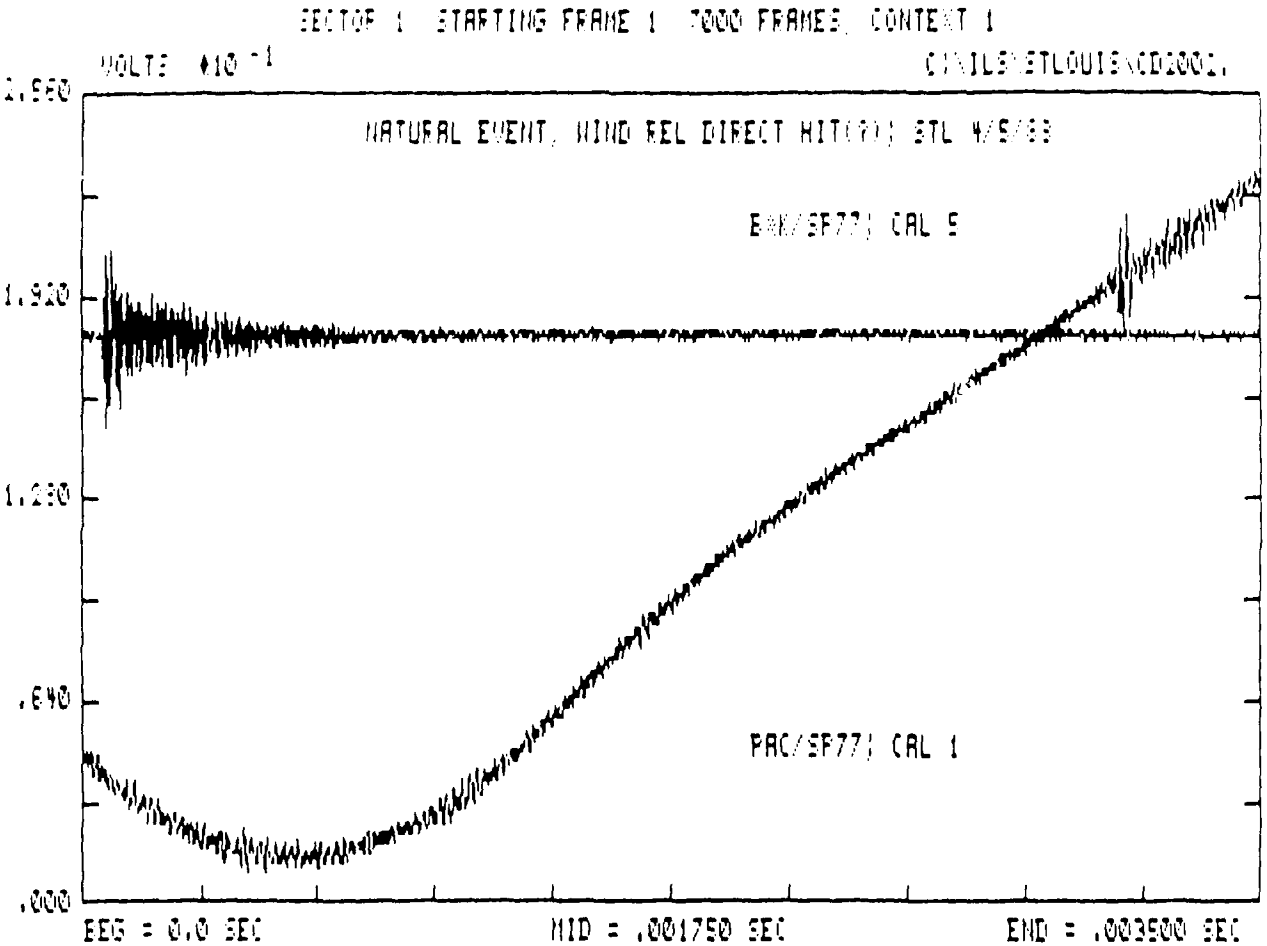


Fig. 7.105. Example 3 of high frequency waveforms at SP77

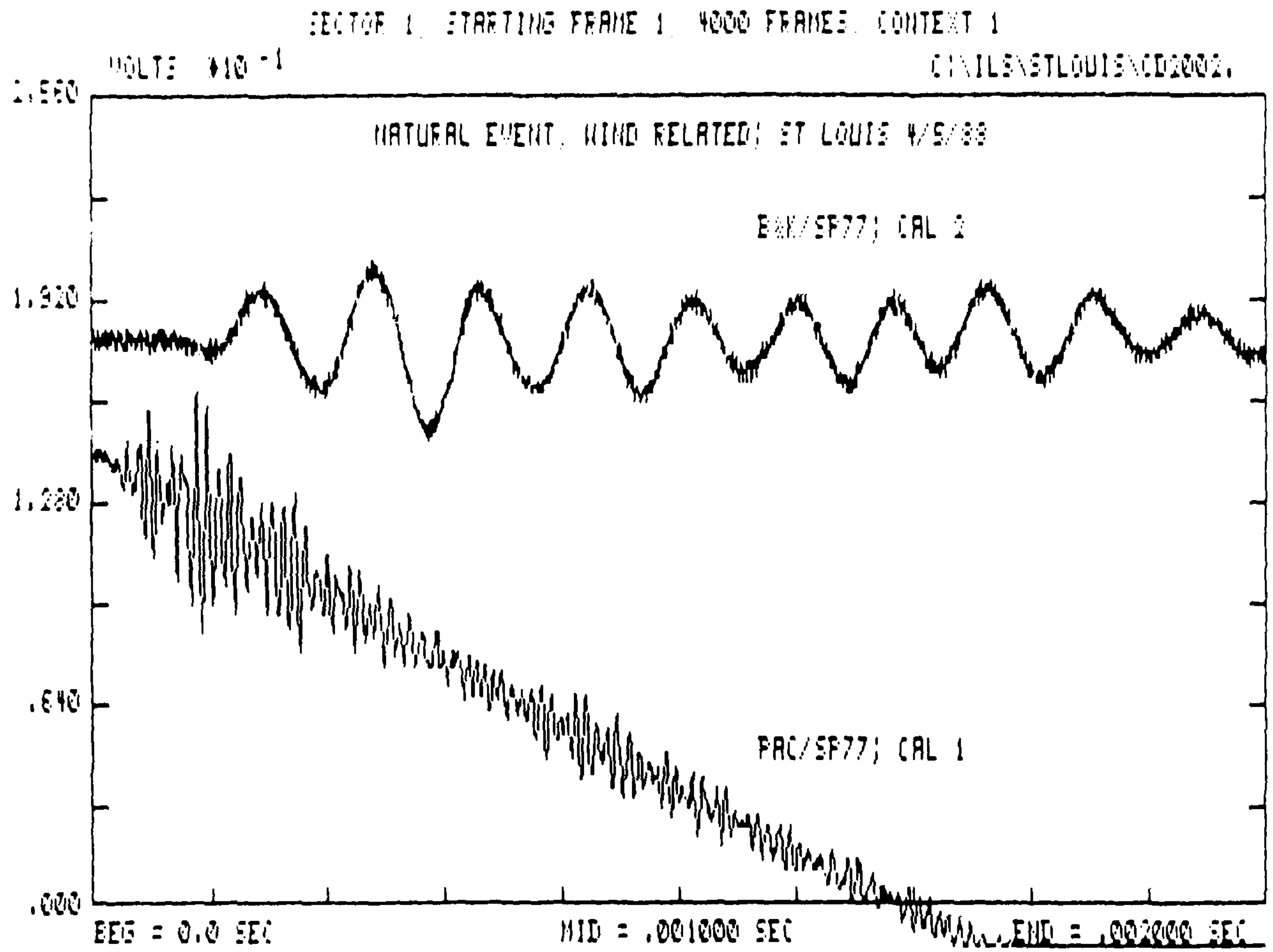


Fig. 7.106. Example 1 of waveforms of low frequency event recorded at SP77 by B&K and PAC accelerometers

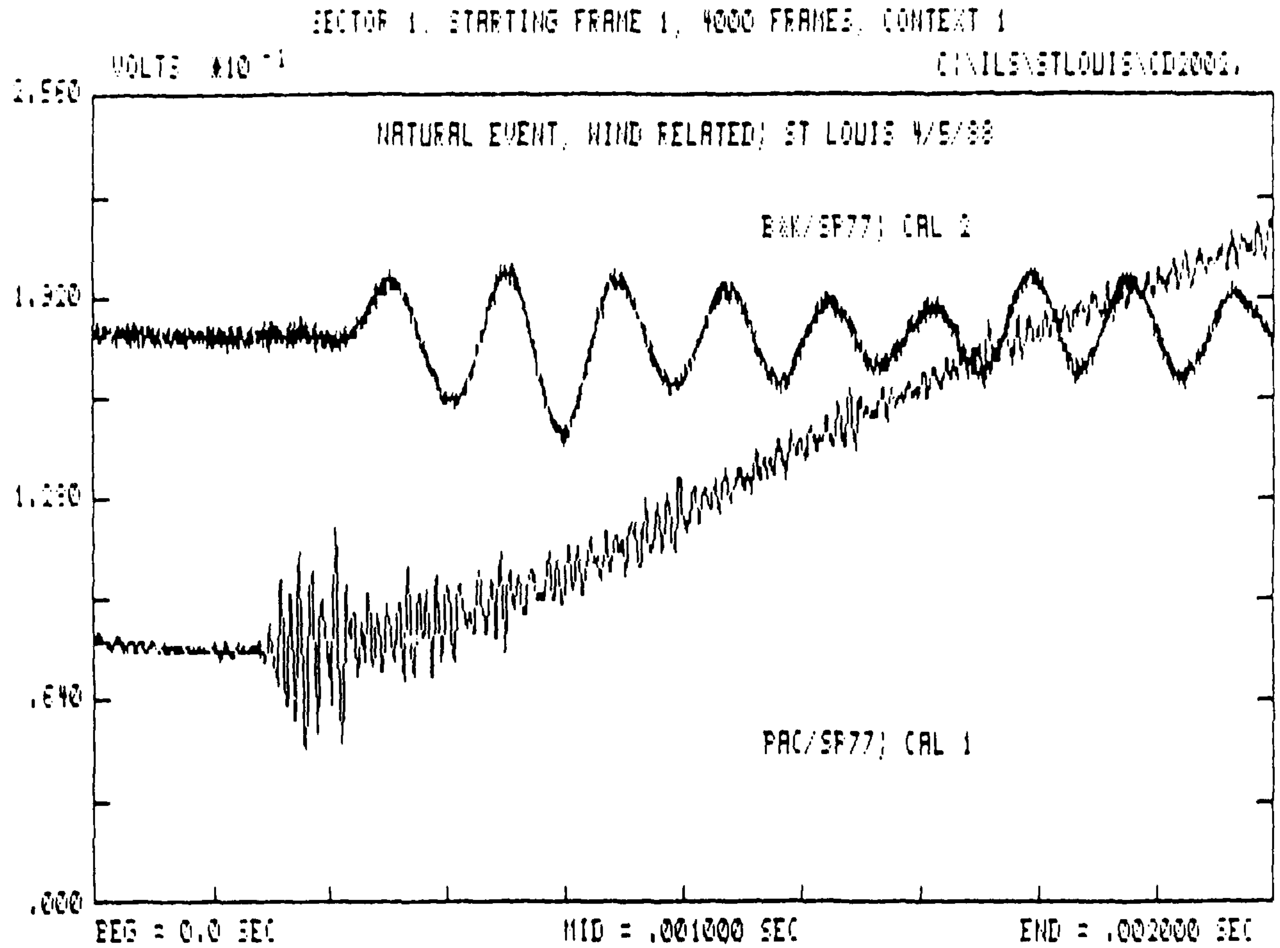


Fig. 7.107. Example 2 of low frequency waveforms at SP77

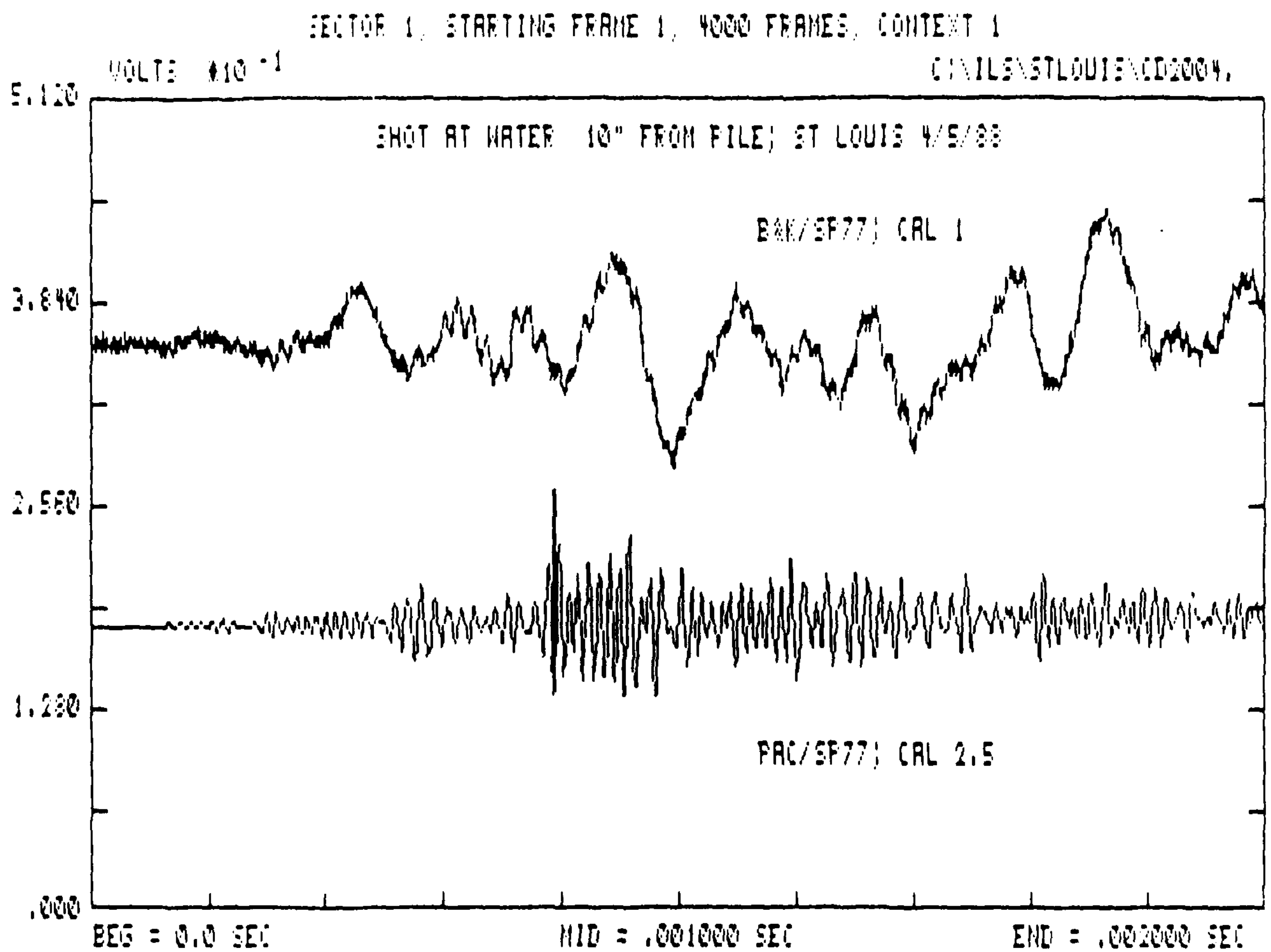


Fig. 7.108. Parallel record of a BB shot at water 10 in. from SP77 sheetpile

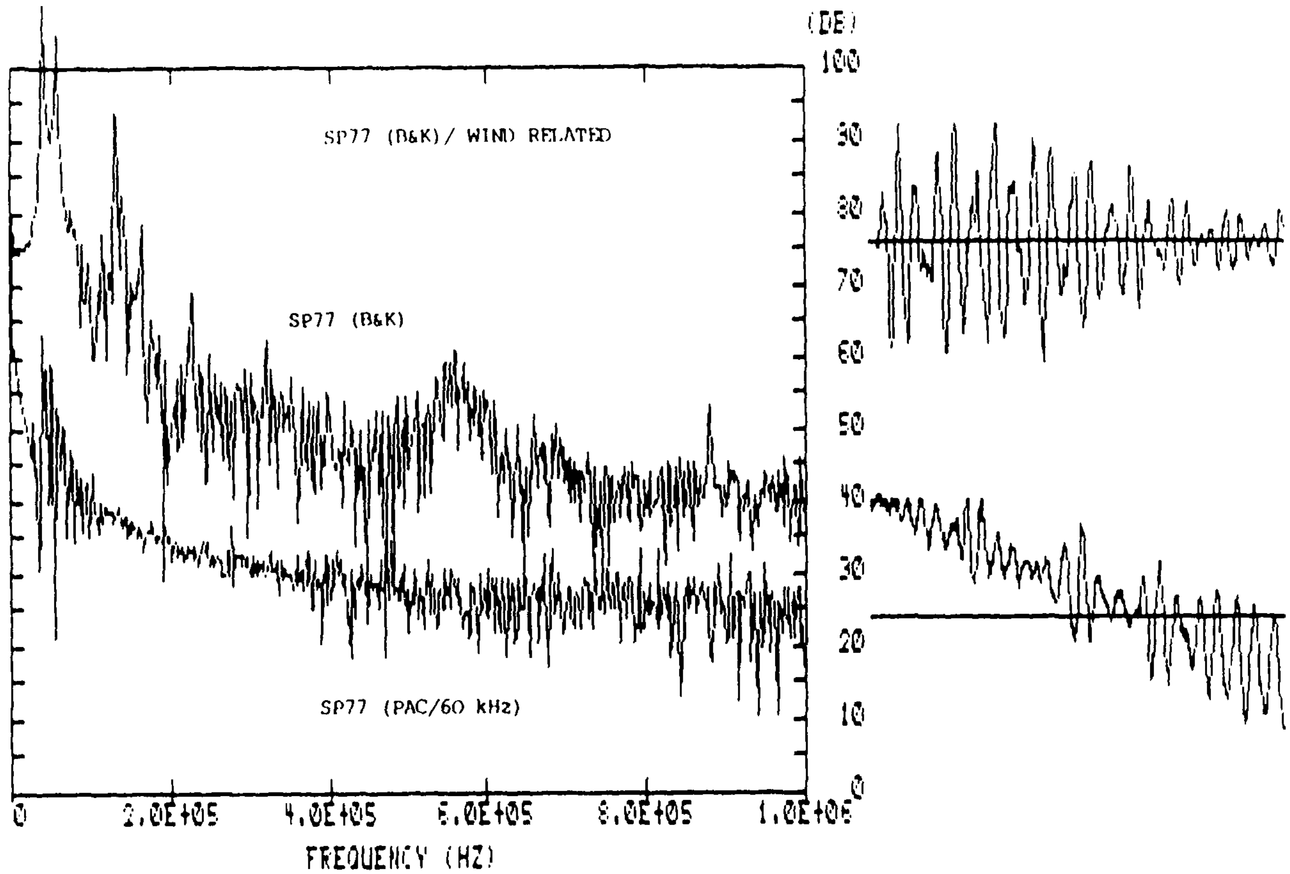


Fig. 7.109. Frequency response at SP77 to a moderate frequency natural event as recorded by B&K and PAC accelerometers

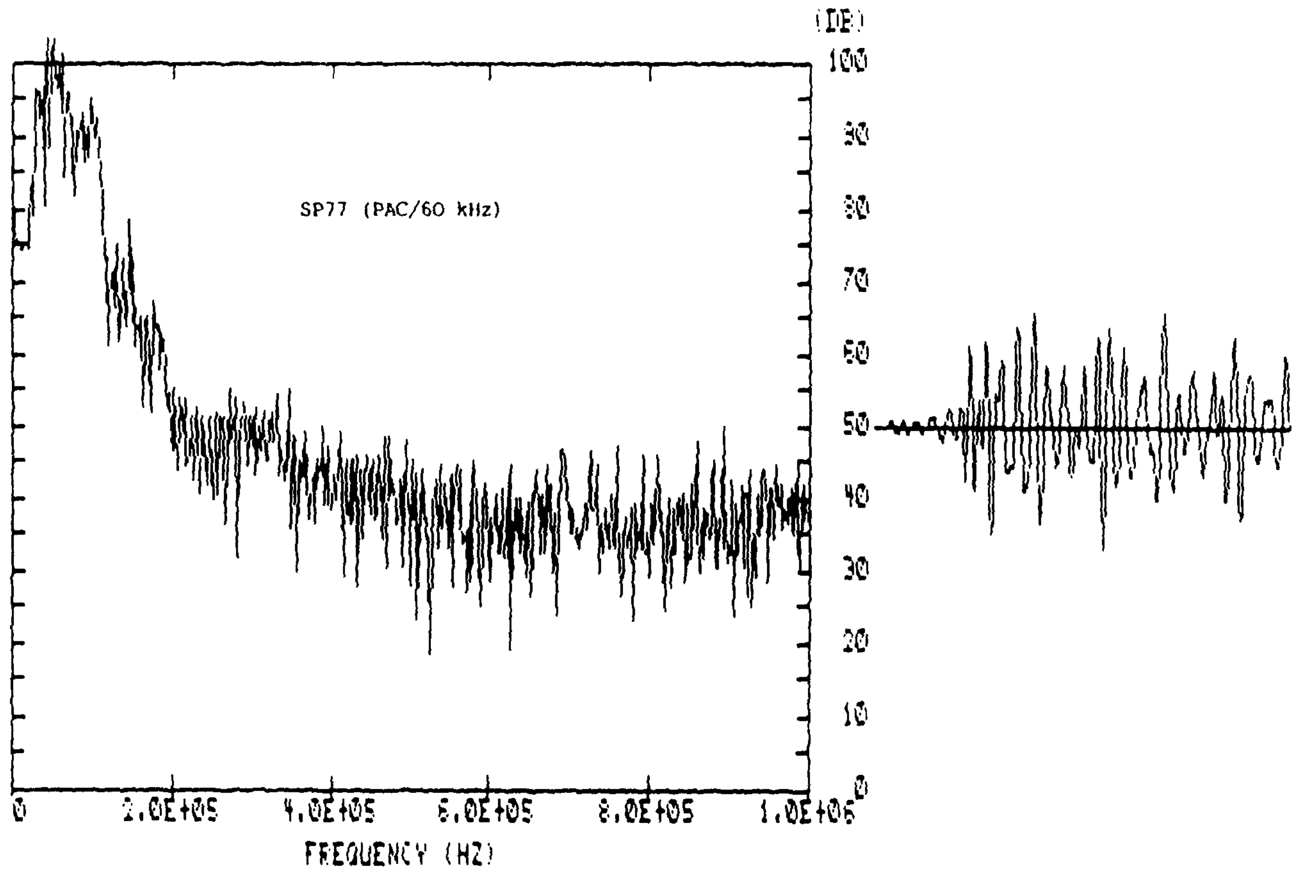


Fig. 7.110. Frequency response at SP77 to another moderate frequency natural event recorded by PAC accelerometer

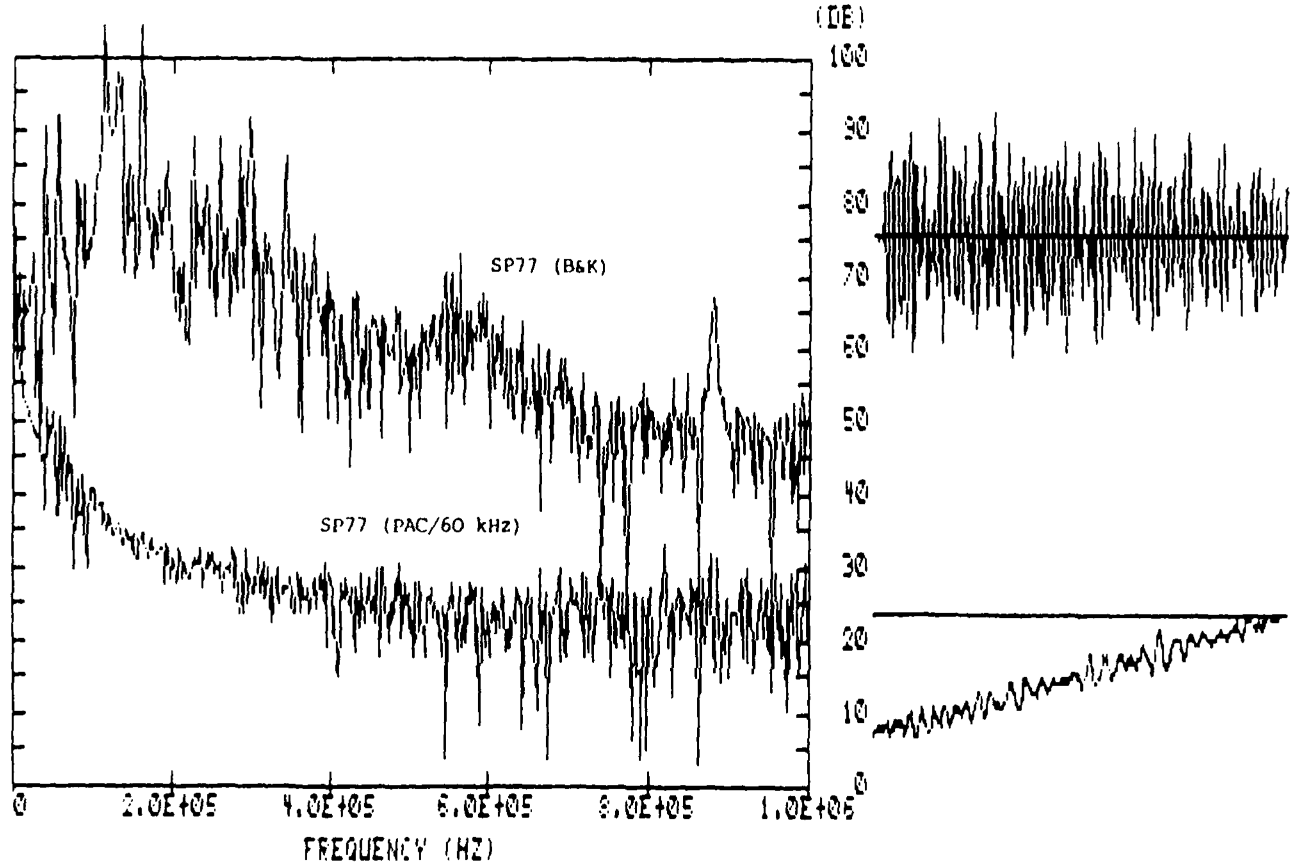


Fig. 7.111. Example 1 of frequency response at SP77 to a high frequency natural event as recorded by B&K and PAC accelerometers

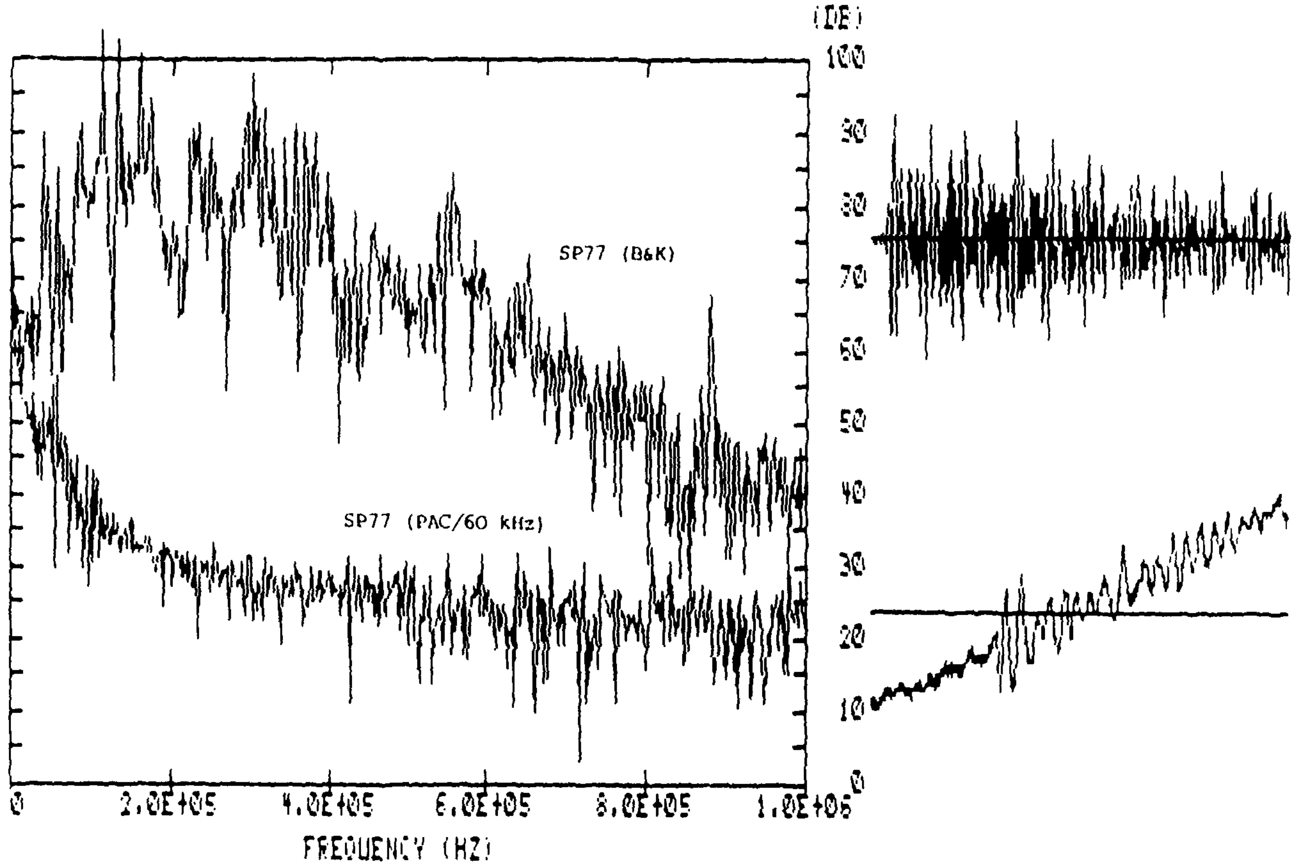


Fig. 7.112. Example 2 of frequency response at SP77 to high frequency natural event

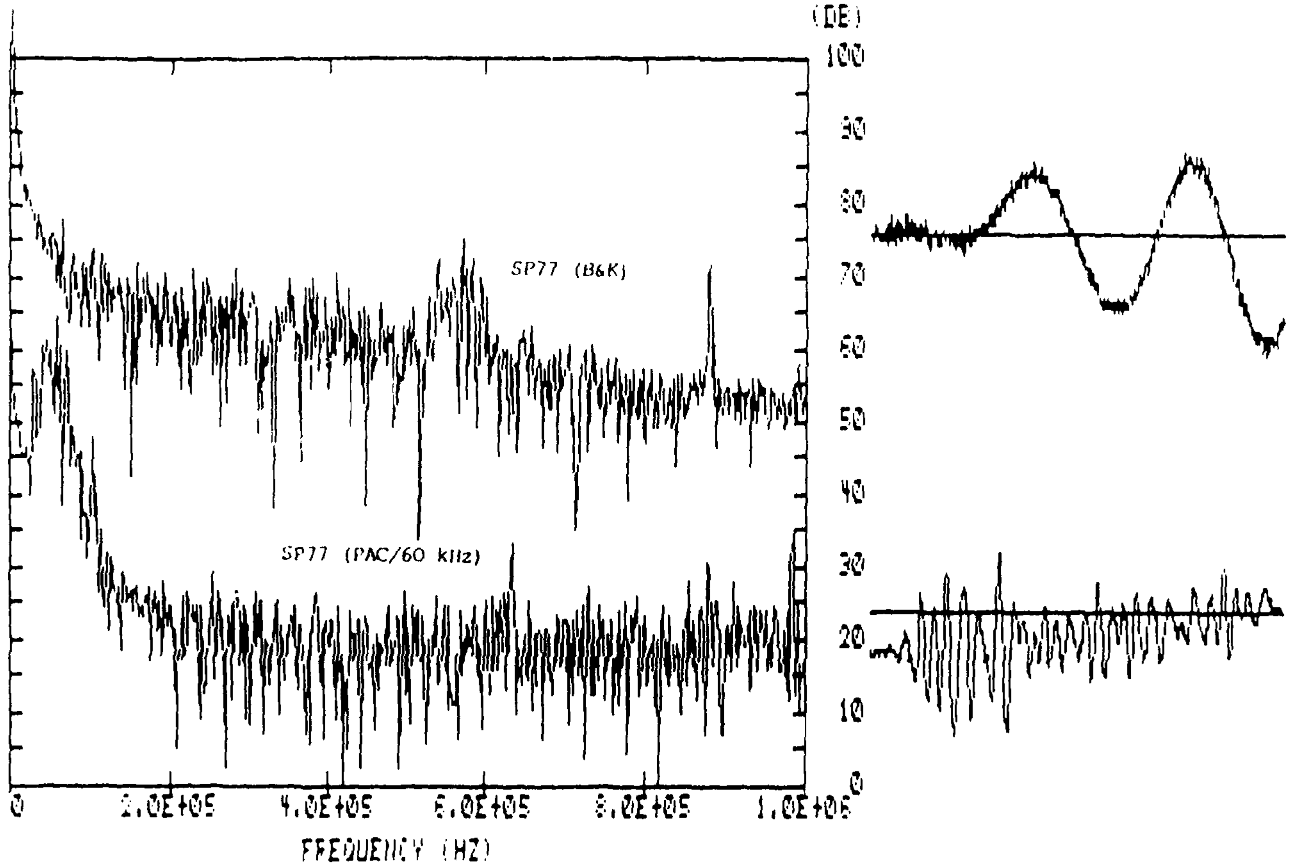


Fig. 7.113. Example 1 of frequency response at SP77 to a low frequency natural event as recorded by B&K and PAC accelerometers

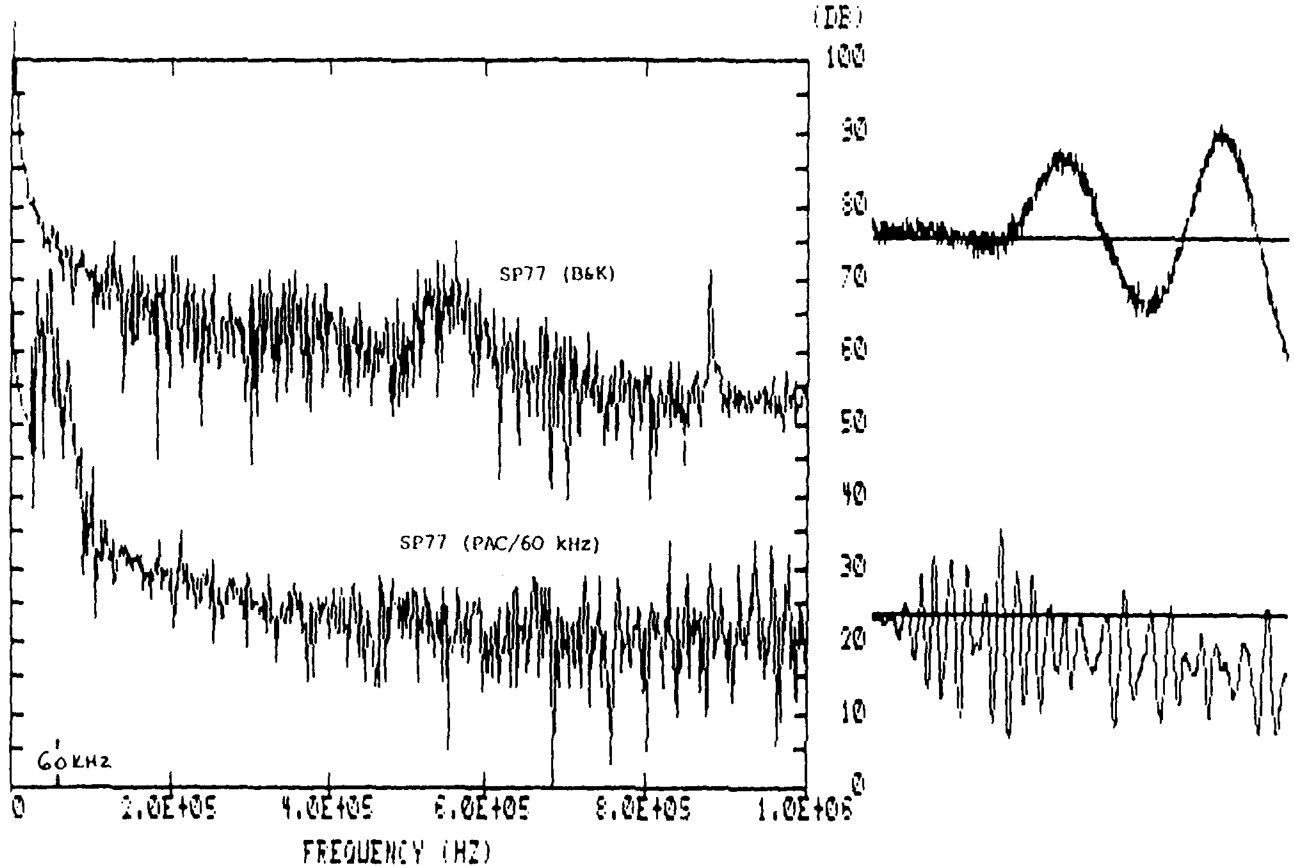


Fig. 7.114. Example 2 of frequency response at SP77 to low frequency natural event as recorded by B&K and PAC accelerometers

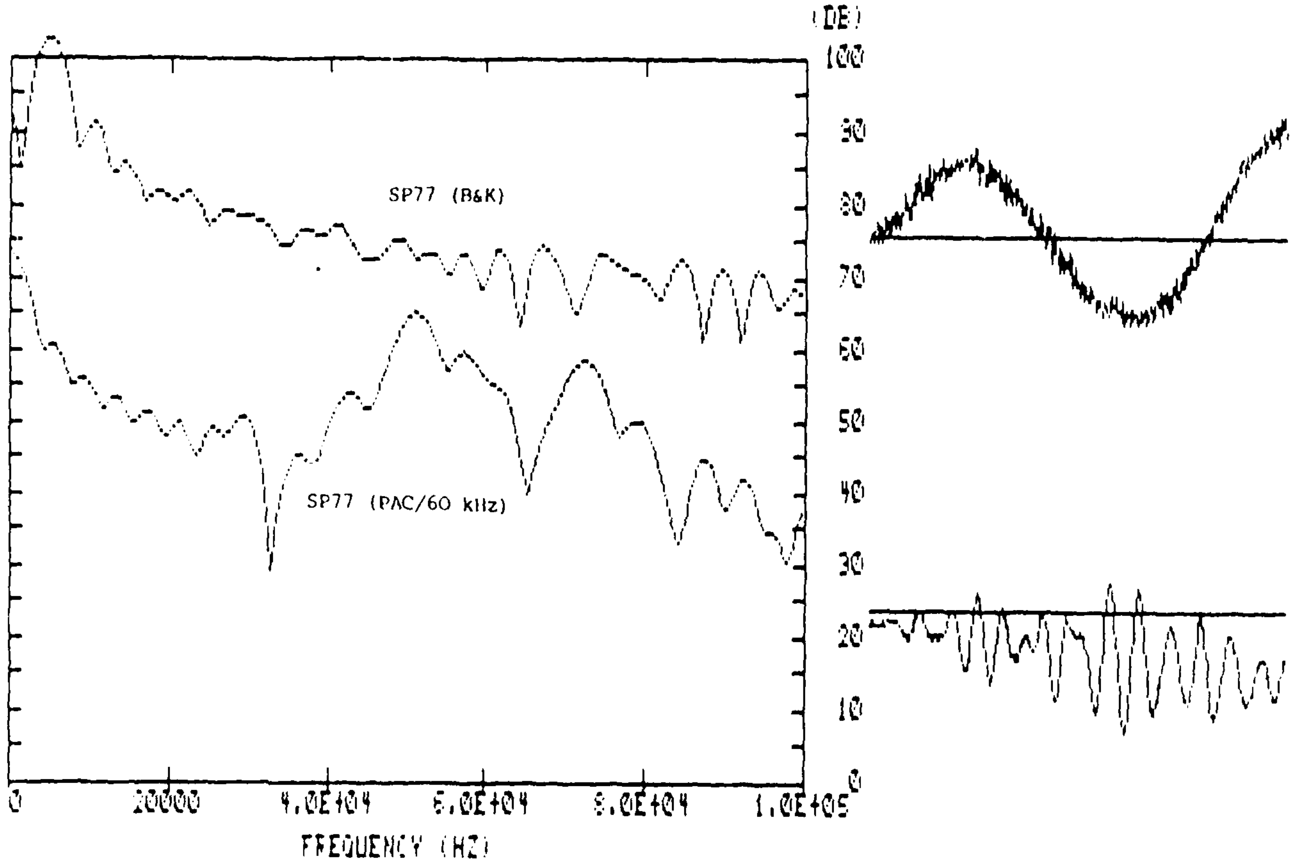


Fig. 7.115. Detailed frequency response to low frequency event

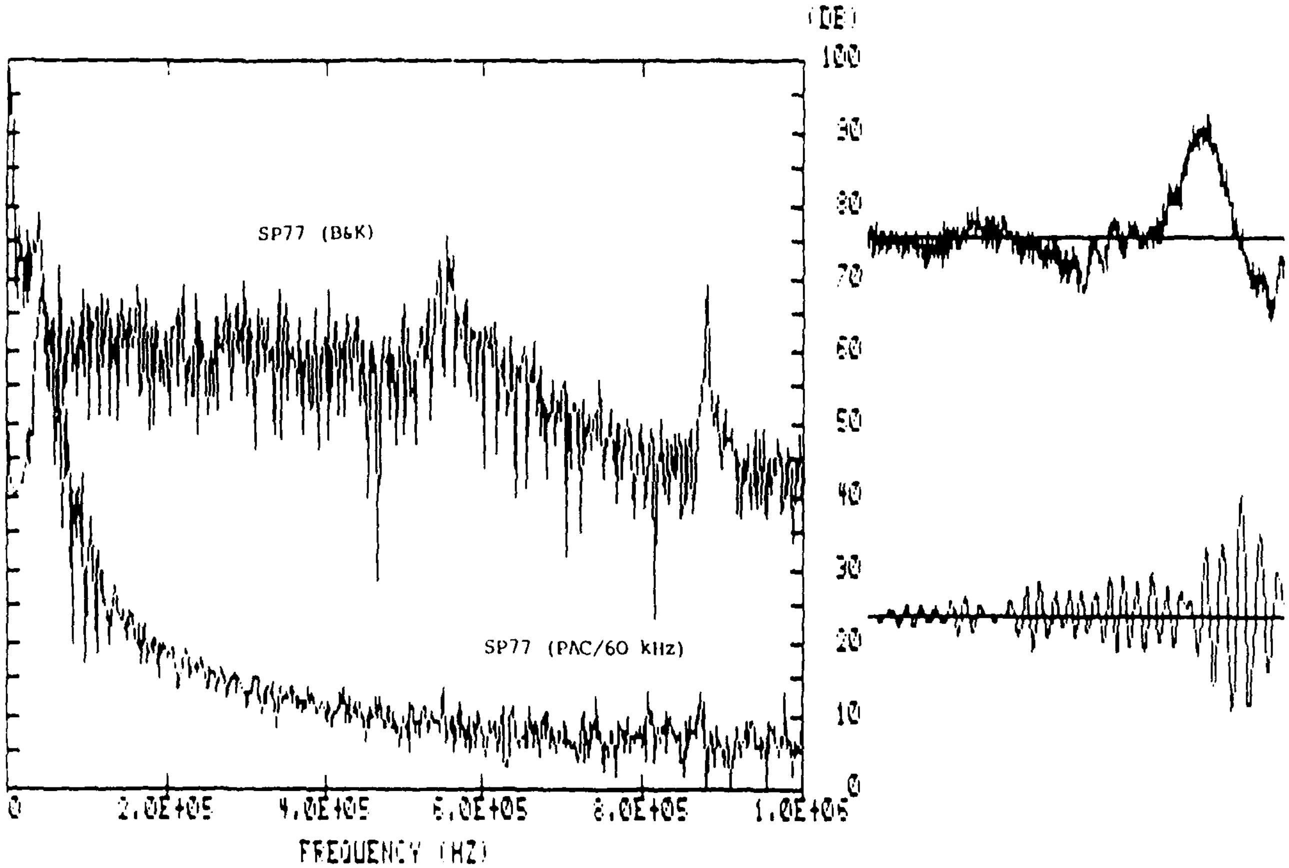


Fig. 7.116. Frequency response to a shot at water as recorded at SP77 by B&K and PAC accelerometers

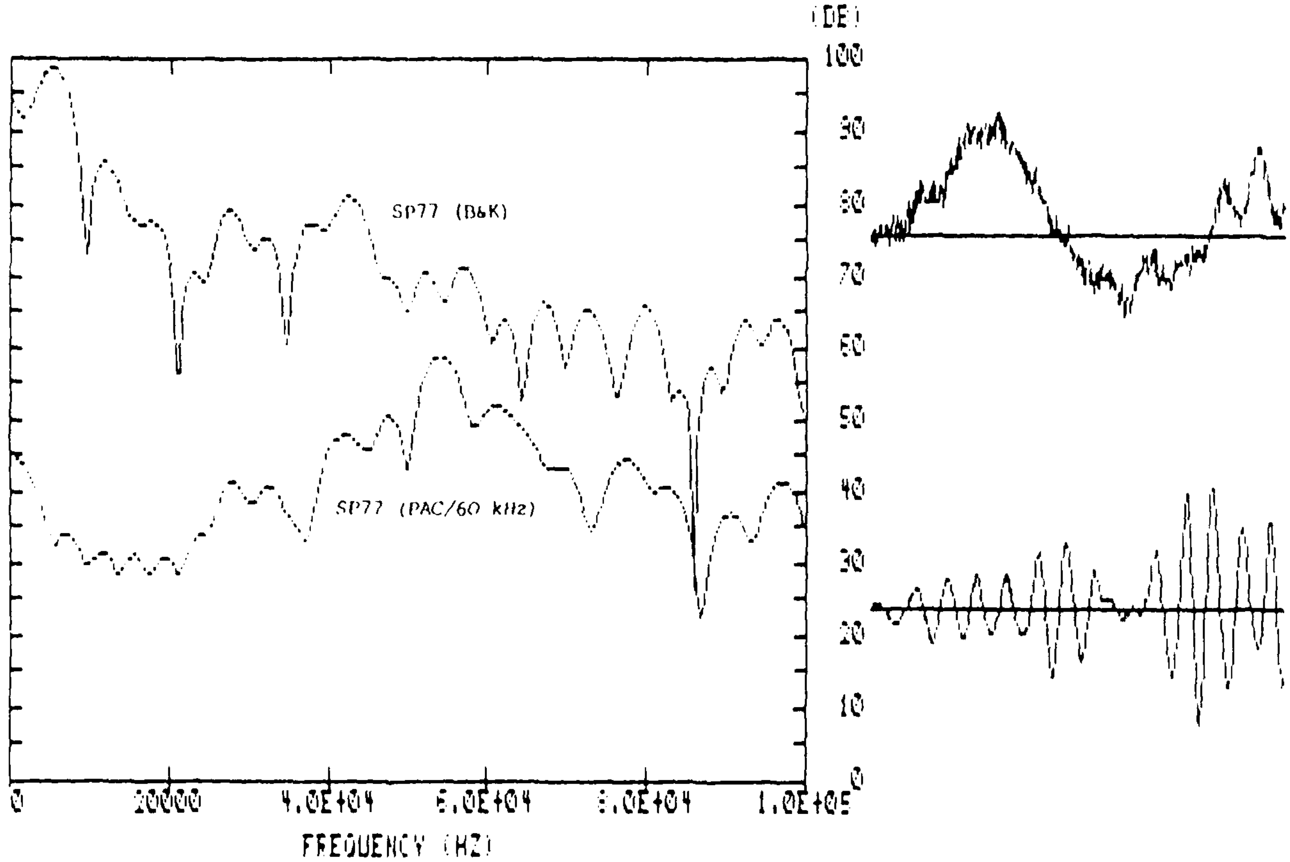


Fig. 7.117. Detailed frequency response to the shot in water

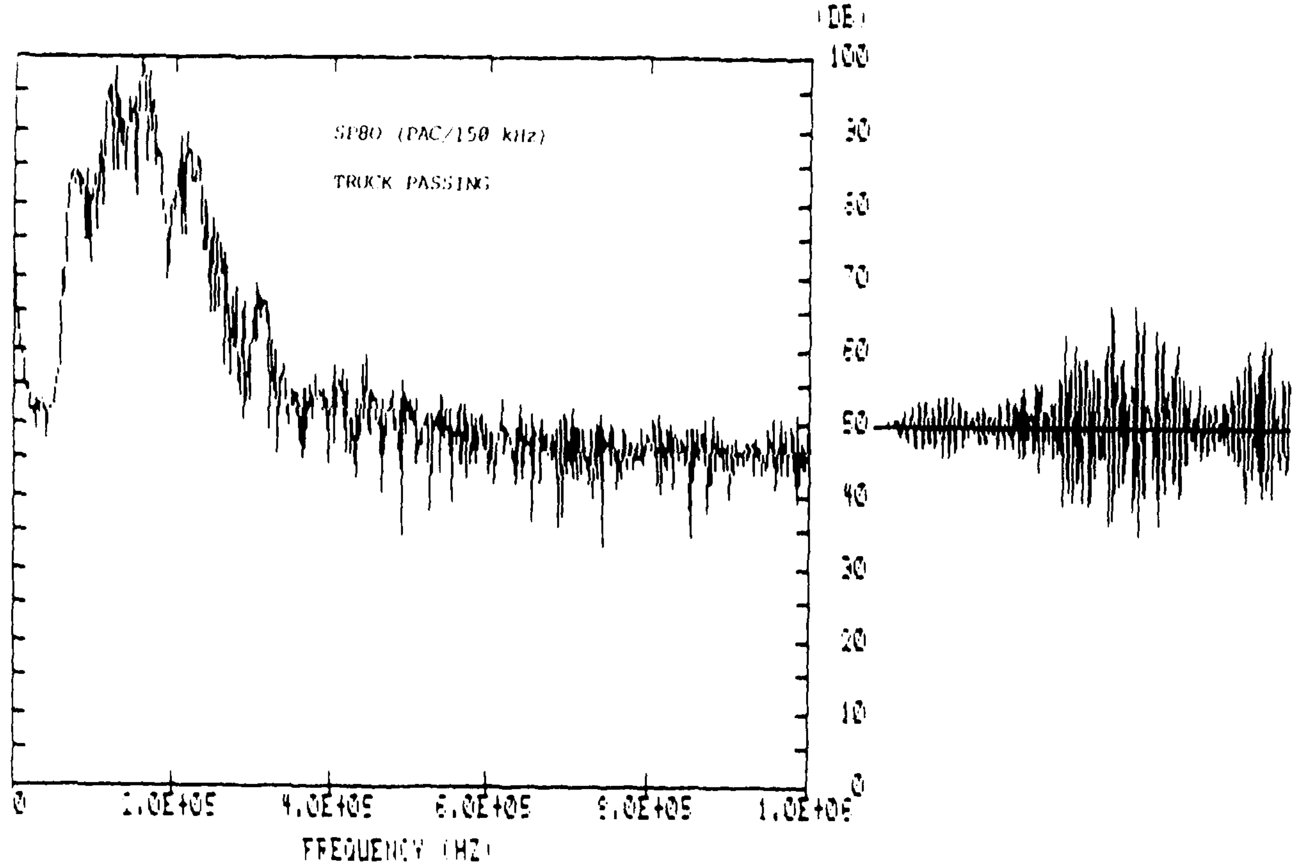


Fig. 7.118. Frequency response to a truck passing by PAC accelerometer at SP80

8.0 ANALYSIS

8.1 Initial AE Monitoring: All Cells

8.1.1 Introduction

During the initial period of AE monitoring, the characteristics of the cofferdam as a whole were defined by measurement of the AE activity of each of the main cells, seven (7) back-up cells, and one independent third stage tie-in cell over a period of 5 months (March through July, 1986). A total of 62 cells were monitored; some on only two occasions, others on as many as seven occasions.

To better identify particular regions of the cofferdam and to provide a basis for meaningful discussion of the AE characteristics peculiar to that region, a brief discussion of the theoretical loading distribution follows.

8.1.2 Cofferdam Loading Distribution: Theoretical Considerations

Two dimensional, incompressible, irrotational fluid flow theory suggests the following brief considerations for a body immersed in a steady flow.

Using Figures 4.1 and 4.2 for reference, the upstream leg of the cofferdam would be expected to experience the maximum dynamic loading, had it not been for the presence of the flow deflector system anchored at cell 92. This should relieve much of the dynamic loading as well as provide a steadier (less turbulent) flow into the upstream navigation channel. The temporary closure system anchored to the connecting arc between cells 14 and 13 will

perform a similar function for the flow entering the Missouri channel as it approaches the First Stage Dam structure.

The flow downstream from cell 92 increases in velocity until the "venturi throat" is reached in the vicinity of cell 87. This implies a decrease in loading reaching a minimum at cells 87-85. Thereafter, the flow expands rapidly causing an increase in loading with further downstream motion.

Maximum loading would be anticipated in the region bounded by cells 82 and 78 where the flow becomes fully expanded. It is anticipated that the remaining river leg cells (77-71) would experience a relatively constant load level.

High dynamic loading would be expected at the corners of the downstream leg of the cofferdam due to powerful vortices shedding from the mainstream; more so at the end of the navigation channel where the flow is more turbulent and the corner sharper.

8.1.3 AE Data Analysis

8.1.3.1. Summary Of AE Activity

The average values of AE, recorded as counts/min (C), events/min (E) and C/E, for each of the main cofferdam cells monitored during the period are shown in Figure 7.9. It will be seen that certain groups of cells (e.g. 67-69, and 86-93) exhibit a generally higher activity than the nominally constant base level (e.g. cells 48-51 and 71-77) and some regions are noticeably far more active (e.g. cells 59-61 and 78-81).

These observations are discussed below.

8.1.3.2 AE Data Summary: River (Navigation) Leg

Close inspection of the AE activity for the upstream and river (navigation) legs of the cofferdam shown on Figure 7.9 indicates good general correlation with the theoretical loading distribution implied in Section 8.1.2 above. The departure from "theory" at the region bounded by cells 86 through 82 can probably be explained by the high concentration of back-up cells behind cells 89-85 and the third stage tie-in cells adjacent to cell 82. These would be expected to absorb a significant measure of the load applied to the main cells.

Of particular note is the peak activity consistently recorded at cell 80. This together with the other river leg cells of significance will be the subject of more detailed analysis in Section 8.2.

8.1.3.3 AE Data Summary: Downstream Leg

The minor peak of AE activity at cells 68 and 69 is probably attributable to the turbulent flow expected in this region due to the powerful vortices shedding from the mainstream flow around the downstream corner of the cofferdam dam. Had cell 68 not been "supported" by additional local cells associated with construction of the downstream guide wall the AE activity would probably have reached a higher level than that shown.

8.1.3.4 AE Data Summary: Missouri Leg

In considering the Missouri leg of the cofferdam, which is experiencing relatively steady flow conditions, the AE activity is seen to be reasonably constant with one major exception. The

abrupt rise in AE activity for cells 59 through 61 is completely out of character. The reason for this is not known. However it can be speculated that the results shown are not representative since they are based on very limited monitoring in this area of the cofferdam.

8.1.3.5 AE Data Summary: Upstream Leg

AE activity is seen to be at a constant level for cells 95 and 94, and at a value not too much greater than the overall cofferdam base level of 2 to 3 counts per event. Cell 92 activity is considerably higher, approaching a value of five C/E, which is probably indicative of the "noise" being transmitted from the deflector plate structure. A portion of this activity would be expected to transfer to cells 93 and 91 also.

8.1.3.6 AE Data Summary: Back-Up Cells

The back-up and interlocking third stage tie-in cells whose AE activity is shown on Figure 7.10 appear to be contributing significantly to overall structural integrity of the cofferdam dam. Back-up cells 81-87 are registering levels of AE which are consistent with the ratio base level of 2 to 3 C/E established for the main cells. Note that the ratio increases with downstream direction, consistent with increasing loads on the main cells as the flow expands along cells 86, 85, 84, etc. The third stage tie-in cells 99 and 98 at cell 91 are probably contributing significatnly to providing increased reaction to the forces being applied in the region bounded by cells 93 through 90. AE activity for cell 99 has been monitored at a level of 3 to 4 C/E as shown

in Figure 7.17. Similarly, third stage tie-in cells 101 and 100 at cell 82 are significantly reducing the load on main cells 83 through 81 which might otherwise have been anticipated to show levels of AE more like cells 80 through 78. AE activity was not monitored for cell 101.

8.1.3.7 AE Data: Variation With Time

Figure 7.11 shows all AE (discriminated) data obtained during the initial phase of monitoring plotted on a real-time basis. Each data point represents the mean value over a 30 minute monitoring session. For clarity, only a few of the more isolated data points are labelled with their relevant cell numbers. Figure 7.12 shows the same data, but categorized this time to indicate the time of day when the AE monitoring was carried out. It is clear that the time of day of the test has little bearing on the overall AE activity in the cells. However, the envelop of AE activity represented by the extreme outlying data is of interest. For this reason it is considered pertinent to record the actual time-of-day of AE monitoring, thereby assuring an increase in the "population data density" and perhaps a better opportunity to interpret trends.

8.1.3.8 AE Data: All Measured By Region

Figures 7.13 through 7.17 show all AE data obtained during the initial phase of monitoring in more detail and for various areas of the cofferdam. Each data point represents the mean AE activity monitored during a 30 minute test. Figure 7.13 shows the consistently higher values of C/E obtained for cells 80, 81, and

91 during the period. Figure 7.15 indicates that the relatively high C/E values obtained in March for cells 59, 60, and 61 are isolated and were not repeated during a subsequent test in May, 1986. As indicated previously, the relatively infrequent testing of these cells may well have caused the average values indicated in Figure 7.9 to be artificially inflated.

Figure 7.16 indicates a peak of AE activity for cell 92 in late March; interestingly this coincides with the timeframe when the deflector plate attached to cell 92 was probably undergoing mechanical deformation leading to the severe damage it experienced in mid-April, 1986.

8.1.4. PMP Data Analysis

Figures 7.54 through 7.57 show the Pile Movement Point (PMP) data for each area of the cofferdam during the initial AE monitoring phase. This data, furnished by the COE project office, clearly indicates the mean movements of the top of each cell which has PMP instrumentation installed. Figures 7.58 through 7.61 show the relative movements of each side of certain individual cells in more detail. These are cells on which the PMP instrumentation is installed at inboard and outboard locations. Clearly, the cells are undergoing considerable deformation. The lateral movements, into and out of the cofferdam represent the bending forces being applied by changing river elevations. The "squeezing" of some cells such as cell 87, Figure 7.60 as evidenced by the relative shift of inboard and outboard PMP data is probably caused by cell torsional resistance to eccentric loading applied to the cell by differential movements of adjacent cells. Such distortion,

whatever causative mechanism, will produce acoustic emissions.

Indication of the movement of the cofferdam as a whole is given in Figures 7.62 and 7.63 which are included for reference. These show all available PMP data for the months of March through August, 1986.

Figure 8.1 shows the relationship between cell movement (from PMP data) and the river head (river/cofferdam elevation differential) for cell 91 assuming a constant cofferdam base elevation of 357.00 MSL NGVD. While this information is useful in assessing trends, more detail is required for acoustic emission correlation analysis. For this reason histograms which plot successive data chronologically were prepared for representative cells.

These are shown in Figures 8.2 through 8.4 for cells 71, 87 and 91. It is clear from these histograms that although the profiles are quite different they directly reflect the influence of river head on cell movement.

As might be expected the movement (deflection) of cells 87 and 91 increases steadily as river head rises to 64 feet and the resulting hydrostatic force on the cofferdam increases commensurately. This movement reverses as river head decreases but unexpectedly increases again at a river head in the range of 47 to 51 feet to duplicate the maximum deflection reached at a 64 foot head. Cell 71 on the other hand shows greatest movement at river head values of 51 and 60 feet. This departure from expectation is probably due to its location at the downstream corner of the cofferdam.

8.1.5. Correlation of AE, PMP And River Head Data

The correlation of AE, PMP and river head data recorded during this stage of the Study is shown for cells 67, 81, 87, 91 and 92 in Figures 8.5, 8.6 and 8.7. As indicated above the deflection of cells 87 and 91 is generally directly related to river head although the scale of Figures 8.5 through 8.7 is such tht this is not clearly evident. The relationship of AE data and river head shown in these Figures does not have the consistency of the PMP data. Instead it appears somewhat random; at times increasing with increase in river head and at other times exhibiting just the opposite characteristic. The data for cell 91 shown on Figure 8.6 demonstrate this quite clearly. The AE C/E ratio is shown as approximately 9.5 at a river head of 54 feet on April 2 and April 30, 1986, despite a decrease in deflection as shown of Figure 8.4. As river head rose to 63 feet on April 21 and deflection increased to almost the maximum value shown on Figure 8.4 acoustic emission C/E decreased substantially to 2.5 and maintained this value on June 4, 1986, as river head and cell movement decreased. The data shown for the other cells is similarly inconsistent.

8.2 Semi-Continuous AE Monitoring: Selected Cells

8.2.1 Introduction

During this stage of the Study, certain river leg cells of the cofferdam were selected for closer scrutiny. These cells (68, 71, 80, 87, 91, and 92) were monitored on a semi-continuous basis during August and September, 1986. Although semi-continuous, the

frequency of testing was such that each of the cells was monitored for 2 hours per day on an almost daily basis. Such concentration of testing, however, required modifications to the techniques used in the initial phase of monitoring.

Semi-continuous monitoring provided an opportunity to Study AE activity in far greater detail than hitherto. Results obtained during this concentrated effort are discussed below.

8.2.2 AE Monitoring Techniques: Semi-Continuous Monitoring

The availability of two AE monitoring units enabled the testing of two cells concurrently. Further, the recording of only one AE parameter (see below) instead of two (counts/minute and events/minute) as in the initial stage, meant that each cell pair could be monitored for a continuous period of two hours per day. Because of its greater sensitivity to instantaneous changes in acoustic activity level the parameter counts/minute was selected as the basis for all AE monitoring during this stage.

Cell pairings (68/71, 80/87, 91/92) were selected on the basis of their relative location within the cofferdam; implying an expectation of similar AE activity characteristics for each cell in the pair.

The accumulated AE counts for each 15 minute interval during a two hour monitoring session, were recorded and subsequently converted to a counts/minute value for that interval. The mean value of counts/minute for a given day was then computed by averaging the eight interval values.

Due to unavailability of the second AE unit following the testing on September 3, 1986, subsequent AE monitoring was limited

to the testing of only one cell in each cell pair.

8.2.3. AE data Analysis

A summary of the mean AE activity for the cells under test during the period is shown in Figures 8.8 and 8.9. It will be seen that each cell in a given pair exhibits essentially the same AE characteristic; thus providing a degree of confidence in predicting AE activity in those cells for which monitoring ceased on September 3, 1986.

The general characteristics for cells 80/87 and 91/92 are similar, showing a steady increase in activity until mid-August, a peak value between August 14 and 20, 1986, and a reasonably constant level thereafter until late September when a noticeable increase in activity is evident. Cell 92, with the deflector plate attached indicates a substantially higher activity level in the early period.

Cells 68/71 at the downstream corner of the cofferdam exhibit a characteristic which is far less steady in nature, although the general level of activity remains the same. It is suggested, again, that these cells are undergoing more dynamic loading than the river leg cells due to the powerful vortices shedding from the mainstream in this region.

Instrumentation sensitivity is indicated in Figures 7.18 and 7.19 which show for cells 68, 80, and 91 the relationship between the mean values of AE counts/minute and the mean standard deviation of the data. These indicate confidence in the data obtained.

For reference, Figures 7.20 and 7.21 show the results of a

typical day for the same cells including all data obtained during the two hour tests. The nature of the AE characteristics is discussed below.

8.2.3.1. Cyclic Characteristics Observed In AE Data

The cyclic nature of the AE characteristic has been a noticeably repeatable feature of the two hour monitoring sessions and was investigated further as described below.

Cell 80 was monitored for a continuous period of six hours to Study the AE characteristic in more detail. The results of this test are shown in Figure 7.22 on both a "time from start" and "time-of-day" base. The river elevation during this test which was conducted on September 30, 1986, was 416.5 and was to continue to rise rapidly thereafter.

The six hour test again indicated the cyclic AE characteristic with periodicity ranging from 40/50 minutes to 70/80 minutes. The amplitudes of the signal are greatly increased from the September 23, 1986 test, and the mean value considerably larger. These levels of activity are consistent with increasing river turbulence as well as increasing hydrostatic loads imparted to the cofferdam due to the higher river elevation.

Note the relatively constant value of normalized (Counts/P) AE activity for both tests and the excellent relationship between data means and standard deviations.

8.2.3.2 Normalization Of AE Data

Normalization of all data obtained during August and September was achieved by using the mean pencil-break test value

of AE counts obtained prior to each of the two hour monitoring sessions. This relatively simple daily procedure provided a crude indication of the AE activity level existing at the time of the test, as does the AE equipment floating threshold voltage level (a function of background noise) which is also obtained prior to each test. Obviously, acoustic emissions are more sensitive to changing (dynamic) environmental conditions, than to stable (static) conditions although the possibility of post-activity residual noise due to continuing cell-fill material settlement or stress relieving processes should not be overlooked.

The normalized data for the period is presented, for all cells under test, in Figure 7.23. Disregarding the early September values, which are influenced by unexplainably large pencil break test values, it will be seen that the data collapses to a nominal value of 0.35 ± 0.1 counts/minute/P.

8.2.4 PMP Data Analyses

The pile movements (PMP) are shown in Figures 7.64 and 7.65 for the cells of interest. Where data is not available for a particular cell the adjacent cell movement is shown.

Note should be taken of the relative movements of the inboard and outboard stations in addition to the overall mean movements. Reference to Figure 7.64 also gives an indication of how torsional loads may be transmitted through the connecting arcs to adjacent cells. Note how the cells on either side of cell 90 are simultaneously moving in opposite directions.

8.2.5. Correlation Of AE Data With River Elevations

The AE data obtained during the semi-continuous monitoring of cells 68, 71, 80, 87, 91 and 92 is repeated in Figures 8.11 through 8.13 which also indicate the corresponding changes in river elevation and the rates of change of river elevation, d(RE)/dT. Change in river elevation is shown relative to an arbitrary datum; the elevation at commencement. The d(RE)dT values are an approximation due to the length of periodicity of measurement (i.e. more or less one day). There is clearly a measure of correlation between the AE counts/minute and the scaled d(RE)/dT.

The following detailed discussion concerns just one of the test cells, cell 80 which was chosen because of the greater amount of available data. However the observations may be applied to any of the remaining five cells.

It will be observed in Figure 8.12 that, generally, the greater the rate of change of river elevation, the higher the AE count rate observed. The approximations to d(RE)/dT noted above will inevitably cause a "shifting" of its value relative to real time and this must be considered when Studying the actual correlations. However, the trends for both parameters correspond remarkably well.

Closer inspection indicates that steadily increasing or decreasing d(RE)/dT imparts a corresponding response in AE. Rapid increases in d(RE)/dT involve almost instantaneous rises in the level of AE. Decreases are not so dramatic, probably due to residual acoustics, although it is evident that the rate of change

of AE decreases rapidly. To observe these trends in more detail, the rate of change of AE, d(C/M)/dT, was correlated with d(RE)/dT and this is shown in Figure 8.14 for cell 80. Given the approximations involved in computing rates of change from relatively sparse data, it will be seen that the correlation is excellent.

8.3 High Water Period Monitoring: Selected Cells

During early October, 1986 extremely high river levels occurred. Concern for the safey of the cofferdam and its operation resulted in a decision by the St. Louis District to intentionally flood the facility to preclude the development of a "quick" condition at the locks and dam foundation and to prevent overtopping of the structure. As a result, unexpected and exceptional data was accumulated for conditions in which the cofferdam was,

(a) Approaching and sustaining near maxumum loads.

(b) Undergoing rapid loading relief.

(c) Experiencing controlled reloading during the subsequent dewatering process.

The configuration of equipment used and the semi-continous monitoring techniques employed to measure acoustic emissions during this period were identical to those described in Section 8.2.

8.3.1 High Water Stages

As noted above the river level rose rapidly during the latter part of September, 1986. This resulted in much higher AE activity

than previously observed. During early October, 1986 this trend continued as shown on Figure 7.3, with the river almost reaching the elevation of the record flood of 1973. At the immediate location of the Locks & Dam 26 (Replacement) project, the river crested on October 9, 1986 at 429.6 MSL NGVD, only a few inches below the top elevation (430 MSL NGVD) of the cofferdam sheetpile cells.

As described previously, concern for the safety of the installation and its operation prompted the decision to intentionally flood the cofferdam. This was commenced on October 7, and completed on October 9/10, 1986.

Subsequent dewatering of the cofferdam began on October 12, 1986 when it was determined that the river level was receding. The dewatering was completed in early November, 1986.

A schematic of the sequence of events during the flooding and dewatering processes is shown on Figure 8.15.

A second peak in river level occurred on October 30, 1986 as also shown on Figure 7.3. Although of lesser magnitude than the first, it will be shown that the AE method again was able to measure the response of the cofferdam to this event.

8.3.2 High Water AE Monitoring

The results of monitoring carried out in October and November are shown in Figure 7.24. Note that for each cell the AE value is the mean of several readings observed over a 20-minute period as more fully described in Section 8.3.2.1. The very high values of AE counts/minute are several orders of magnitude greater than

those measured at any time during the preceding seven month Study period.

Access to the cofferdam during the first ten days of the flood stage was limited due to the river conditions and safety measures established by the St. Louis District Corps of Engineers. This resulted in relatively sparse data in the early days of the flood event. However, the record is nearly continuous for cell 80 and from this it is reasonable to infer that AE activity reached a peak sometime between October 4 and 7, 1986. This is consistent with river level approaching its crest on October 9 and the intentional flooding of the cofferdam which began on October 7, 1986. More discussion on the correlation of AE with environmental effects is presented in Section 8.3.4

Monitoring of cells 68, 71, 80, 87, 91 and 92 resumed on a regular basis on October 15, 1986. As shown in Figure 7.24, all data recovered for the remainder of the period is contained in a fairly narrow band of decreasing AE activity. Cell 68 is consistently the least active of the six cells, and Cells 80 and 87 are the most active.

A uniform rate of activity was recorded by mid-November and the general levels of AE measured at the end of November were vitually identical to those for September and earlier periods. The data recorded from October 2 through October 15, 1986 is somewhat scattered with a maximum of approximately 400,000 counts/minute for cell 80 and a minimum of about 20,000 counts/minute at cell 71. Nevertheless, both values are substantially above AE activity recorded previously.

8.3.2.1 Daily Monitoring: Typical Results

Section 8.3.2 above discussed the observed trends of the daily values of AE measured. Individual measurements are reviewed in this section.

Each of the six cells was monitored for a minimum period of 20-minutes per day when testing was possible and AE Counts accumulated every 60 seconds within this period were recorded. The means and standard deviations of the data are therefore based on a nominal twenty measurements per cell.

Figure 7.25 indicates typical daily trends of measured AE levels for the period October 2 to October 5, 1986 for Cell 80. The fluctuating characteristic of the signal reflects the intermittent nature of structural adjustment in the cell. The recording method used was such that each data point only represents accumulated AE counts during that one-minute period.

8.3.2.2 Accuracy of Data and Equipment Configuration

Due to the large unbalanced loads applied to the cofferdam, consideration must be given to the possibility that the AE system was overdriven by the highly active conditions existing through much of this period.

The equipment and testing techniques employed throughout the AE monitoring of the cofferdam were established as a result of preliminary surveys conducted in February 1986, when relatively calm conditions prevailed. A caveat must be posted, therefore, with respect to the actual or absolute values of the measured AE count rates. This does not imply that the data is invalid, but indicates that trends and general order of magnitude levels of AE

activity may be more significant than any individual count/minute value.

8.3.2.3 Equipment Threshold Voltages

A further confirmation of trends in AE data monitored was given by automatic threshold voltage settings of the AET 2046R equipment as described in Section 6.2.2.7 and shown schematically in Figure 6.3.

Figure 8.16 shows the values of threshold voltage previously encountered during the August-September 1986 monitoring. The mean threshold is seen to be of order 1.15 V, rising to approximately 1.25 V at the end of that period. Figure 8.17 on the other hand, extends the period to include the high water monitoring. Note that the vertical scale is compressed by a factor of ten. The dramatic increase in threshold voltage in early October reflects the surge of background noise generated within the cellular structure as the river rises to maximum elevation and flow. The threshold generally decreases after October 7, 1986 as the cofferdam is flooded and the river falls.

8.3.3 PMP Data Analysis

Pile Movement Point (PMP) data supplied by the Corps of Engineers' Project Office has been analyzed in detail and is shown graphically in Figures 7.64 through 7.70 and Figures 8.18 through 8.21. Since it is obvious that significant deformation occurred within the cofferdam cells as the river rose, it is considered important to correlate these movements with AE data obtained.

8.3.3.1 Measured Cell Movements

Figure 7.64 shows the moderate cell movements occurring across the cofferdam during August, a relatively 'quiet' period. In contrast, the first weeks of October produced much more deformational activity as shown in Figures 7.65 and 7.66. For clarity, complete data is shown only for the navigation channel cells. For these cells negative values indicate movements into the cofferdam. Note that for each cell there are a pair of readings, the first being the motion of the inboard section of the cell, and the second, the outboard section. Relative movement of the inboard/outboard sections and between adjacent cells are an indication of lateral compression (squeezing) and eccentric loading (torsion) respectively. A close inspection of Figure 7.65 shows that the general motion of all cells along the navigation channel, except cell 91, was intitially into the cofferdam as expected. This movement was then reversed on or shortly after October 6, 1986, despite the continuing rise in river level. The rates of movement between October 1 and 5, 1986 are less than that for the single day following. It would appear that most of these cells were experiencing maximum stress conditions in the period leading up to October 5, 1986 at which time yielding may have occurred. As will be discussed later, this coincided with the time-frame during which peak AE values were measured.

Generally, the cell movement was again into the cofferdam between October 8 and 9, 1986 as shown on Figure 7.66. Interestingly, this was during the period in which the cofferdam was intentionally flooded. Completion of flooding occurred late on

October 9, 1986 at almost the same time that the river reached its crest. Previously measured maximum cell movements were repeated or only slightly exceeded at this time.

Cell 91 displayed quite different movement characteristics than its neighbors; an important observation which probably explains its uncharacteristic AE signature.

8.3.3.2 Cell Movement Histograms

To summarize the above discussion and to concentrate on those cells which had PMP instrumentation installed, histograms have been prepared for Cells 95, 91, 87 and 71. These histograms, which plot the cell movements chronologically as a function of river head differential are shown in Figures 8.18 through 8.21. Although not AE monitored, Cell 95 is included because it exhibits a clear, uncluttered histogram, thus enabling a clearer discussion of general trends.

Figure 8.18 shows the displacement history for Cell 95, and indicates that although a fairly confined envelope of activity occurred in the March-September period, the rising river level in early October resulted in large and increasing movements into the cofferdam. This growing displacement was successfully arrested by the deliberate flooding of the cofferdam and the still-rising river level caused only small further movement. Note that under equilibrium conditions (river head approximately zero) it is possible to identify the extent of 'permanent set' accumulated in this cell since the original surveys were conducted in the early part of 1986. New datums were established for future PMP surveys between October 10 and 15, 1986. The right-hand profile therefore

represents the daily cell displacement during the cofferdam dewatering process. The fluctuating inward and outward motiion appears to correspond with:

a) the river level which was initially decreasing, then increasing again to a second peak on October 30, 1986 and,

b) the water level inside the cofferdam which was decreasing throughout at a fairly constant rate.

Figures 8.19 through 8.21 are histograms for Cells 91, 87 and 71, and broadly speaking the above comments remain applicable. The relatively 'closed-loop' system depicted in Figure 8.19 for Cell 91, reflects the lesser deformation occurring in cells which have additional structural support from adjoining third stage tie-in cells, in this case, cells 98 and 99. For the period October 3 to 6, 1986, Cell 91 displayed a movement profile opposite to that characterized by the other cells of this group. The above observation lead to the expectation of a different AE signature for this cell.

The histogram for Cell 87 as shown on Figure 8.20 is typical of a mid-channel circular cell, and particularly one with back-up cells in close proximity. Cell 71, Figure 8.21, at the cofferdam's downstream corner is seen to be generally moving out of the cofferdam with the re-application of loading during the dewatering process.

8.3.4 Observed Trends of AE

8.3.4.1 Introduction

Before addressing actual correlation analyses, it is necessary to discuss the observed trends of measured AE with the cofferdam response to high water loading.

The hydrostatic loading on the cofferdam cells is directly related to river head differential which is the most significant parameter in any attempt to correlate the AE data. However, in addition to the static loading other dynamic forces should be considered. For instance, earlier AE monitoring indicated that the rate-of-change of river level was a second order term in the algorithm describing the response of the structure and hence the AE characteristic. In addition, certain flow conditions of the river are more conducive to turbulance and vortex/eddy formation. Also, it is quite likely that under flood conditions, the flow and river bed conditions and characteristics were changed, perhaps permanently. Unfortunately, the data collected is insufficient to ascertain or quantify these effects but the possibility of their existence should be borne in mind.

8.3.4.2 Trends Of AE With River Head And d(RH)/dT

The principle of 'correlating' AE activity with rate of change of river head, d(RH)/dT, was introduced earlier and it was determined that it was broadly reasonable to do so. However, reservations were made with regard to the accuracy of the method on the basis of the low frequency of data collection. Bearing in mind that acoustic emission occurs instantaneously following a

deformation, correlation with a parameter (river level) which is measured on a daily basis must be viewed with caution. This subject is discussed in more detail below.

8.3.4.3 Importance of Data Measurement Frequency

Figure 7.8 shows river levels for the period immediately preceding the crest on October 9, 1986 during which they were measured on an hourly basis. This is the only available data for river levels measured at this frequency. However, it is definitely applicable to this discussion. The non-linearity of the data is immediately apparent, implying that the actual d(RH)/dT is varying considerably in a given 24-hour period. Figure 7.8 also presents the same information for the AE monitoring window which was ordinarily between the hours of 9:00 am and 5:00 pm. This plot also shows the continually changing river level during the periods when AE measurements were being made.

It can be inferred that instantaneous acoustic emissions actually measured in a given 20-minute period would be partly dependent upon the slope of the river head change characteristic during that period.

8.3.4.4 Overall Trends of AE Data With Cofferdam Loading

From the above discussion it is suggested that if there is a correlation between measured AE and river elevation and/or its rate of change, it wil be only approximate. If, however, the physical response of the cofferdam to continually changing environmental conditions is included in the correlation the overall picture will become clearer.

Section 8.3.3 discussed the PMP data in some detail, and it was shown that the cofferdam cells react somewhat inconsistently at times.

In this context, consider the AE measurements for Cell 80 shown in Figure 8.22. The peak AE on October 4, 1986 occurred at maximum d(RH)/dT. On this date the cells were probably experiencing maximum stress prior to an apparent 'yield' on October 5, 1986. The rising river level caused hydrostatic loading to increase further, resulting in further AE activity. This is seen to reach another peak on October 8, 1986 when the cofferdam was approximately half full due to flooding. Unfortunately data for october 9, 1986 is not available. The subsequent decrease in AE is due, presumably, to the growing equilibrium conditions as the river head approached nominal zero as well as to falling river level.

Dewatering of the cofferdam commenced on October 12 and was completed on or about November 6, 1986. During this period hydrostatic loading varied as a result of falling river level and decreasing water level inside the cofferdam. Figure 8.23 shows the relative rates at which these processes were occurring, and it will be seen that for a considerable period of time between October 12 and October 27, 1986, d(R)/dT and d(RH)/dT were in opposition, and the influence of the latter was dominant.

Figure 8.24 combines the d(RH)/dT and d(R)/dT trends with the measured AE activity for both Cell 80 and Cell 92. Note the change in scale compared to Figure 8.22. It will be seen that correlation between AE and d(RH)/dT is as anticipated. The same

may be said of data obtained for Cells 87 and 91, shown in Figures 8.25 and 8.26. The rather different AE characteristic for Cell 91, particularly in the early period, is best explained by its unusual movement profile. This is probably influenced by the two adjoining third stage tie-in cells (99 and 98) all of which are situated inside the cofferdam.

8.3.5 Correlation/Regression Analyses of AE Data

8.3.5.1 Introduction

The previous section addressed the observed trends in measured AE data, and indicated the correlation between AE activity and the principal forces acting on the cofferdam structure. These forces are absolute river elevation and the rate of change of differential river head. River elevation provides static load on the normally dewatered cofferdam and the rate of change of differential river head results in dynamic loads.

The data correlation or regression studies which follow are based on the observed changes in these parameters with time, and they are hereby defined as the independent variables of interest. Attention is also given, where appropriate, to the value of differential river head which is an additional independent variable of significance during the cofferdam flooding and dewatering activity.

The correlation analyses do not include data associated with the physical response of the individual cell-piles as recorded by PMP measurement. Several other potential variables are considered to be contributing only second order effects and due to the

infrequency of data measurement as discussed in Sections 8.3.4.2 and 8.3.4.3.

Throughout the following analyses, AE is considered the dependent variable, and for convenience is represented by the function Log (AE). Since there is only one variable of interest (AE) and the effects of the independent variables on it are studied, the general correlations are referred to as regression analyses.

All such analysis presented in the following is for Cell 80 unless otherwise noted.

8.3.5.2 Relationship Between Measured AE, RE and d(RH)/dT

Figures 8.27 shows the variation of Log (AE), river elevation and rate of change of river head [d(RH)/dT] with calendar time for the entire August to November 1986 period under consideration.

The correspondence of the data and the similarity of the trends suggests the existence of an interrelationship between Log (AE) and the two independent variables. The relationship of Log (AE) with the various independent variables is presented in Figures 8.28 through 8.34.

Figure 8.28 shows that Log (AE) is strongly related to RE as a measure of river head and that d(RH)/dT is influential although to a lesser extent. The following regression analyses will stress this observation.

8.3.5.3 Linear Regression Analyses

Although the relationship between AE and RE would not be expected to be a linear function, a linear regression analysis was performed to provide a baseline of information. Figure 8.29 shows the linear regression of Log (AE) and f(RE-400), where RE-400 is used for convenience. The regression line is represented by,

$$\text{Log (AE) est} = 0.19359\ (\text{RE}-400) + 0.58286$$

The correlation coefficient (R) and standard error (se) of the estimate are 0.8967 and 0.764, respectively, which are surprisingly good. A multiple regression analysis using both independent variables produced marginally better results as might be expected ($R=0.8989$, $se=0.762$). This result confirms that inclusion of d(RH)/dT marginally improves the correlation, but more significantly does not degrade it.

Closer inspection of the data shown in Figures 8.29 indicates a difference in the relationship of measured and estimated Log(AE) for the period following cofferdam flooding and as when the river levels were receding and dewatering was underway. Figure 8.30 shows the regression output with chronological 'data paths' superimposed. As a result of this observation, each data set was analyzed separately and the resulting linear regression line is shown in Figure 8.31. For the period prior to October 9, 1986 the correlation coefficient (R) is 0.9039 and the standard error (se) is 0.654. For the period after that date, $R=0.7218$ and $se=0.478$. The standard errors are significantly less than above.

8.4 Further Semi-Continuous Monitoring: Selected Cells

8.4.1 Introduction

Acoustic Emission (AE) monitoring during the early part of 1987 was directed at developing continuity between the period of high water and flooding (October/November 1986) and the anticipated continuous monitoring with the PAC ATLAS 7016/3000 equipment which commenced in August, 1987.

As before the cells monitored were 68, 71, 80, 87, 91 and 92 along the cofferdam navigation leg. The equipment and procedures used for the semi monitoring were the same as previously described.

8.4.1.1 AE Data Analysis, February to April 1987: Selected Cells

The results of Acoustic Emission (AE) monitoring showed little activity early in the period. However, activity increased with the commencement of the spring flood season towards the end of March, 1987. The measured AE levels are shown in Figures 7.26 and 7.27 and the corresponding river elevations in Figure 7.4. As shown on these figures, river elevation rose gradually during March and April causing a similar increase in the overall AE activity. This is more obvious in the logarithmic presentation shown in Figure 7.28.

As can be seen in Figures 7.26 and 7.27, moderately high water of March 30/31, 1987 and on April 15/16, 1987 during which the river rose to elevation 413+ and 415, respectively, caused an observable increase in AE activity. The AE spike on March 17,

1987 is due to heavy wind gusting, as discussed below. Figure 8.31 in which AE activity for Cell 80 and river elevation are shown chronologically for the period indicate that even during low river stages measured AE closely reflected relatively small changes in river elevation and the consequent hydrostatic loading on the cofferdam.

Summary AE data for all six cells is shown in Table 7.1. The average measured counts/minute were derived from the results of monitoring each cell for a period of approximately one hour. Table 7.2 shows the same data after selective discrimination to take account of excessive input from local tug, barge and wind gust noises. The discriminated AE data is shown graphically in Figure 7.27. A logarithmic presentation on Figure 7.28 gives a clearer contrast between the behavior of specific cells. Cells 80 and 87 exhibit the highest levels of activity and cells 68 and 61 the lowest.

This period of spring flood monitoring highlighted two areas of interest. First, an apparent increase in sensitivity of the AE instrumentation to river traffic during higher water conditions. The relative continuity of semi-continuous monitoring has shown that the noise generated by barge and towboat sonar equipment cause a rapid rise in AE as the tow passes. Secondly, wind gusts sometimes reaching 40-50 knots cause a significant momentary increase in AE activity. In this case the acoustic emissions reflect the increased wind loading on the cells.

Figure 8.32 presents a linear correlation of log (AE) with river elevation for the period from February to April, 1987. It

indicates a reasonably good correlation of measured AE activity for the low to medium river level of the period.

8.5 Continuous Monitoring

8.5.1 Introduction

The results of multichannel continuous monitoring are presented in tabular and graphical form in Table 7.3 and Figures 7.30 through 7.53.

As previously described, this monitoring was conducted from mid-August, 1987 to March 25, 1988, using the Atlas 7016/3000 system described in Section 6.3.

As described in Section 6.3.6.2.3 early problems with the data acquisition software resulted in several short duration runs. After resolving these problems, consistent data collection of 22 to 158 hours duration was attained through the period covered in this report, except for four periods as noted above. The periods of monitoring, channel assignment and sensors used are described in Table 6.4.

AE measurements using two sensors (60 kHz and 150kHz) at the same location (two waveguides and one sheetpile) were undertaken to compare low and high frequency sensors. The total events for each time period and the ratio of low frequency (LF) to high frequency (HF) events are shown in Table 7.4. Channels 13 and 7 recorded events from LF and HF sensors on the 50-foot waveguide in Cell 77 (WG-77.50.C). Channels 4 and 8 recorded events from LF and HF sensors on the 30-foot waveguide in Cell 77 (WG-77.30.N)

and Channels 3 and 9 the LF and HF sensors on the sheetpile of Cell 77 (SP-77).

8.5.2 Calibration

As part of the procedures described earlier, the 60 KHz sensors were evaluated for relative sensitivity using a pencil break calibration test. There was excellent consistency for each sensor between individual pencil breaks and between two series of tests. However, the number of events varied depending on the particular sensor. The differences between the highest and lowest events per sensor was approximately a factor of three. Nothing in the calibration sheets provided by the manufacturer would suggest this high a difference in apparent sensitivity. Also, the gain for individual channels was pre-set at manufacture, and unlikely to result in significant differences between channels. The remaining reason for the observed differences, therefore, appears to have been in the mounting condition of the individual sensors. An acoustic couplant was used but apparently the torque applied to the sensors by the connecting cables was enough to cause variations in the quality of the bond to the test plate. These tests were beneficial in identifying the critical importance of mounting to accurate recording of acoustic signals.

8.5.3 Comparison of 60 kHz and 150 kHz Sensors

In order to facilitate a decision concerning the most desirable sensor, the relative sensitivities of 60kHz and 150 kHz sensors were analyzed. The 60kHz sensor requires a 20 to 100 kHz band pass filter and the 150 kHz sensor a 100 to 300 kHz band pass

filter. As previously indicated, these sensors and frequency ranges will be referred to as Low Frequency (LF) and High Frequency (HF), respectively.

As shown in Table 7.4, the 60 KHz (LF) sensors consistently recorded more events than the 150 KHz (HF) sensors. The average was approximately 4.5 times greater for the LF sensors monitoring the waveguides. Two unexplainable reversals of the LF/HF ratio can be seen to have occurred, specifically on November 13 to 16 and on December 7 to 11, 1987. Except for these reversals, the average LF/HF ratio was 6.5 for sensors attached to sheetpiles, not significantly different from those attached to waveguides. This comparison is shown graphically on Figures 7.38 through 7.41. for the six sensors discussed above.

The principal reason that more LF events are to be expected is higher attenuation at higher frequencies. If this is the case, it would be expected that the amplitudes of the LF events would be higher than for the HF events. A qualitative evaluation of the amplitude plots for each data set shows very little difference in amplitude between LF and HF events. An exception did occur for the data sets of November 3 to 5, and December 7 to 11, 1987 where the LF events show significantly higher amplitudes. Figure 6.12 shows this difference for the December 7 to 11, 1987 period. This lack of amplitude difference is probably due to the fact that the majority of the events recorded during the monitoring period were of minimal strength and barely exceeded threshold values. Another possible reason for the lack of difference between LF and HF

amplitude is the greater efficiency of AE generation in the LF range.

8.5.4 Sensor Type

The following discussion compares the effectiveness of sheetpiles and waveguides as AE monitoring facilities. As stated in Section 8.5.2, it appears that the number of events recorded by a sensor is strongly influenced by the quality and type of mounting used to attach the sensor to the monitoring point. Certain inherent variations, therefore, are to be expected between locations due to mounting and coupling differences. However, some consistent trends were identified beyond expected mounting variations and are discussed herein.

8.5.4.1 Waveguides

As shown on Figures 7.6 and 7.7 there were no significant fluctuations in river elevation during the continuous monitoring period which could cause significant deformation within the structure and consequent increased microseismic activity. The waveguides, which were installed in the fill material of the cells, indicated very little activity during the majority of the monitoring period. However, the AE events recorded at all waveguide stations increased substantially in the latter part of February, 1988 and continued at this increased level until suspension of monitoring on March 25, 1988. Average Events per hour for all waveguide monitoring stations are presented in Table 7.3 and Figures 7.38 through 7.40, 7.42, 7.43, and 7.46 through 7.51. Microseismic events were recorded at an average rate of

less than 2 events per hour prior to late February, 1988 but increased to levels of several hundred to several thousand per hour after that date. This compares with an event rate in the ten thousands per minute level due to the much greater hydrostatic loading of the structure during the high water period of October-November, 1986.

Although two waveguides were not in use, there were seven waveguides at various depths and locations within three different cells for comparison. Event rates were fairly consistent over time and between the various waveguides. The 30-foot waveguide in Cell 76 (WG-76.30.S) provided an exception with event rates about 10% of the average for the other waveguides.

There were repeatable variations in the number of events for waveguides of different depths. As might be expected, the deeper and longer waveguides generally recorded more events. However, Cell 79 provides the exception with an apparent reversal in the expected trends between the 30 (WG-79.30.C) and 50-foot (WG-79.50.S) waveguides.

No identifiable trend was found which could be related to position of the waveguide within the cell, i.e., north, south or center.

Short and long-term coincidence plots were examined to determine if an event or series of events was recorded at different stations at the same time and thus could be assumed to have originated from the same source. The short-term plots were 300 seconds long and had a test point interval of 3 seconds. Short-term coincidence was nonexistent; adjacent waveguides did

not record events simultaneously. The signals measured were of low amplitude, and stronger signals from structural deformation may transmit between waveguides.

Identification of long-term coincidence was not much more successful, since identification of bursts of activity in the very low event rates was difficult. With some "interpretation" and prior knowledge, a degree of coincidence in minor bursts of activity in the November/December, 1987 period could be inferred. The prior knowledge consisted of the incidence of significant rainfall or wind as shown in Table 7.5, which provides a summary of rainfall and wind velocity for the period from November 1 to December 15, 1987. There was a very weak correlation of micro-seismic activity with periods of heavy rain, and at best a tenuous correlation with wind. This actually may be an advantage in using waveguides to monitor cofferdam stability because, as will be seen, sheetpiles are much more sensitive to the "noise" of rain and wind.

Typical long-term trend graphical data is shown in Figures 8.33 and 8.34. Each graph presents events recorded in a 65500 second (18.20 hour) period for the waveguide indicated.

In order to obtain greater uniformity in the mounting of the waveguide sensors a standard 1.5 pound weight was installed on top of the sensor at WG-76.30.S on February 8, 1988 and on all others on February 28, 1988. This weight consisted of a three-inch long, 1.5-inch diameter steel rod. As discussed previously and shown in Table 7.3 and Figures 7.46 through 7.51, average events per hour for the recording period commencing in late February, 1988

increased at all waveguides monitoring stations. This increase was greatest at WG.76.30.S, WG-76.70.C and WG-79.50.S and smallest at WG-77.70.S. The increase was not uniform and the events per hour recorded at the waveguide stations varied substantially, and in fact, returned to 'normal' at WG-77.70.S within a few days. It should also be noted that no increase in event rates was recorded at WG-76.30.S after the installation of the standard weight on February 8, 1988. This possible increase in sensor activity as a result of more uniform and effective mounting appears to confirm the general conclusion concerning the importance of mounting reached previously.

8.5.4.2 Sheetpiles

The number of events recorded at sheetpile stations was considerably higher than for waveguides for both background and burst activity. Event rates averaged approximately 200 per hour, with some bursts generating events at the thousands per hour level. This data is summarized for all sheetpile monitoring stations in Figures 7.41, 7.44, 7.45, 7.52 and 7.53 as well as Table 7.3.

There were 6 sheetpile locations monitored; three on main cells 77, 79, and 80 (SP-77, SP-79 and SP-80); and three on connecting arcs 76/77, 78/79, and 79.80 (SP-76/77, SP-78/79 and 79/80). Event levels were reasonably consistent between the various sheetpile monitoring points, although there were a number of instances in which significantly more events per hour were recorded at one or more sheetpile stations than at others. This relative consistency in event rates suggests uniformity in

sheetpile response as well as generally better and more uniform sensor mounting.

No short-term coincidence in events was found between the various sheetpiles monitored, or between the sheetpiles and the waveguides. This indicates that events generated by the same source were not detected at adjacent sheetpile monitoring stations. This result contradicts earlier tests using a hammer which demonstrated detectability of a high amplitude source up to 1 1/2 cells away but is supported by the frequency analysis test discussed in Section 8.6.

Long-term coincidence was quite good between sheetpile locations. Changes in event activity in one sheetpile were closely mirrored by changes in the other monitored sheetpiles. Several coincident bursts of high event rates were observed at various points during the monitoring period. After obtaining the wind and rainfall records for the appropriate dates, a definite pattern emerged. When the number of events recorded at a sheetpile went over 1000 in a 10-minute interval, weather records indicated a significant rainfall for that time period. When recorded events reached several hundred, but less than 1000, per 10-minute interval, weather records showed winds over 20 mph. It is evident that the majority of activity during the November/December monitoring period was due to rain and wind and not to structural deformation. It is also apparent that this potential source of "noise" can be mitigated by the use of waveguides to verify if the signal source is internal or external to the structure.

There were numerous smaller (less than 100 events per 10-minute interval) bursts probably explained by gusts, unrecorded rain, or local activity. Their low level, however, should have no impact on a stability monitoring program.

One of the most interesting observations during the monitoring period was a reversal of the LF/HF ratio for the sensors at SP-77. The reversal occurred twice, once at the end of the November 13 to 16, 1987 interval, and a second time toward the end of the December 7 to 1, 1987 interval. In each case, the reversals occurred at night when construction activity should be at a minimum. The first reversal lasted about 14 hours, and was not recorded at any other station. About midway through the reversal, a presumed rain induced spike was observed in all the other sheetpile channels. The second reversal occurred in four distinct pulses from 10 to 30 minutes long. There were some minor pulses on the other sheetpiles, but shifted in time from the reversal pulses. Channel 3, which was the low frequency sensor on this sheetpile (SP-77), showed no coincident increase in activity during the reversals. If the increased HF events were indeed high frequency signals, some of the energy should have bled over into the low frequency range and been recorded by the LF sensor. The suspicion, therefore, is that some momentary fault in the system caused the bursts of apparent high frequency events. Their intermittent nature will make this very difficult to confirm.

The expected result of comparing the LF/HF event ratio for the waveguides and the sheetpiles was an estimate of the "source" of the signals. The signals generated by deformation in the fill

material, because of natural filtering, were expected to cause domination by low frequencies in the events recorded on the waveguides. Interlock slippage in the sheetpiles, on the other hand, would create higher frequency events which transmit well in the steel sheetpiles. The presence of the higher frequencies associated with interlock slippage should reduce or cause a reversal in the LF/HF ratio when such slippage is occurring.

Again, because of the fairly static loading conditions for the structure, deformation or interlock slippage did not occur, and confirmation of the above hypothesis was not possible.

8.5.5 Correlation/Regression Analysis

River elevation during the period of continuous monitoring varied from approximately 400 to 411 MSL NGVD. The resulting differential head between river elevation and cofferdam interior varied from 43 to 54 feet. The hydrostatic forces produced by this differential head were not sufficient to generate AE activity of the magnitude encountered in October/November 1986 or even in April 1987. As suggested in Section 8.3.5.3, the correlation of AE with river elevation or equivalent river head, can be effectively analyzed by use of a linear regression analysis. Figures 8.37 through 8.40 present such analyses for the November/December 1987 and January/March 1988 periods. Separate regression lines have been developed for waveguide and sheetpile monitoring stations. The correlation coefficient (R) and standard error of estimate (se) for these analyses show variations. As expected, the fit of the linear regression line confirms the close agreement between these parameters.

8.6 Frequency Analysis

8.6.1 Frequency Response of PAC Recording Channels

The frequency characteristics of microseismic (AE) waves are determined by the nature of their source and the response of the material through which they travel. Detecting/monitoring such microseismic waves at any point within their environment alters their record (waveform) with respect to frequency and phase characteristics compared to the original. The change is caused by the combined response of: (1) the coupling between or mounting of the sensor/transducer and the structure from which the waves are measured, (2) the sensor/transducer itself, and (3) the electronic circuitry between the sensor/transducer and an A/D converter.

Reliable evaluation of AE development within the cofferdam structure monitored at a number of detection points requires the response characteristics of each recording channel to be either known or comparable with each other. This mainly applies to the coupling/mounting conditions since the response characteristics of PAC transducers and the electronic circuitry are known and do not change. A typical frequency vs sensitivity curve for a PAC sensor is given in Figure 8.41.

The results of testing the PAC recording channels using a pencil break at each PAC sensor location indicated consistency in coupling conditions for both 60 and 150 kHz sensors mounted either on sheetpiles or on waveguides. See Figures 7.79 to 7.90. Because of the lack of experimental data, the coupling between fill material and individual sheetpiles was considered similar.

The same assumption is believed to be true for each length of waveguide, i.e., 30, 50 and 70 feet.

8.6.2 Characteristics of Attenuation

The data presented in Figure 7.91 were used to plot Figure 8.42, the attenuation slope versus distance for the dynamics of microseismic waves travelling across sheetpiles from their source (the impact of a BB shot) to the receiver, in this case a PAC sensor/accelerometer on monitoring station SP77. A slope this steep can be explained as a result of a strong joint related loss of transmitted acoustic energy.

The frequency analysis shown in Figures 7.90 through 7.99 indicate a rapid decay of frequencies above 30 kHz for a change in distance from 10.5 to 13.5 feet as the number of joints between the source and the sensor increased from three to nine. The frequency line on the order of 35 kHz, which is dominant in all frequency spectra, was considered related to the response characteristics of the PAC sensor/accelerometer.

8.6.3 Frequency Characteristics of Recorded Events

Parallel monitoring of seismic events with PAC and B&K sensors/accelerometers/transducers installed on the same sheetpile indicated three major types of micro-seismic (AE) events insofar as features of their waveforms in the time domain (Figures 7.101 through 7.108), and in the frequency domain (Figures 7.109 through 7.118).

The most common events of dominant frequency between 50 and 60 kHz, and independent of the type of the transducer, were almost

universally associated with strong wind gusts. Frequency lines on the order of 80,120, and 160 kHz were also present in records from both transducers (Figures 7.109 and 7.110). The steep initial slope of the envelopes of the waveforms recorded by the B&K transducer suggest that their sources were within a few feet of the transducer location. Note the similarities between the frequency characteristics of natural events as recorded from the PAC transducer, and those generated by a pencil break as shown in Figures 7.81 and 7.110.

A second type of events, also related to wind gusts was characterized by an exceptionally wide frequency range from 40 to well over 400 kHz with dominant frequencies on the order of 120, 160, 230 and 300 kHz, as shown in Figures 7.111 and 7.112. Their envelopes as recorded by a B&K transducer, and the lack of a corresponding record from the PAC transducer, suggest events generated by the direct hits of solid particles carried by the wind against the top of the B&K transducer.

A third type of events was characterized by a considerably lower frequency on the order of 5kHz as recorded by a B&K transducer. This record corresponded with a waveform from the PAC transducer with a dominant frequency from 50 to 70 kHz; see Figure 7.115. This event type exhibited a less obvious relation to wind gusts. The frequency characteristics of this event type were found similar to those of a BB shot at the water approximately one foot from the sheetpile on which both transducers were mounted as shown in Figure 7.117.

The only waveform generated by a truck driven along the top

of the cofferdam was recorded by the PAC transducer on sheetpile station SP-80 and is given in Figure 7.118. The frequency characteristics of this signal were comparable to that obtained from the same 150 kHz transducer as generated by a pencil break and shown in Figure 7.82. Dominant frequencies on the order of 120 and 160 kHz were surrounded by 70 and 220 kHz peaks, and a much weaker frequency line at approximately 300 kHz. Note the similar frequency lines, but of different magnitude, present in records from 60 kHz PAC transducers. Note also the envelope of the waveform related to the truck as characteristic of a source in a more remote location from the sensor/transducer. The possibility of triggering a high frequency response from very low frequency vibrations generated by a truck cannot be excluded.

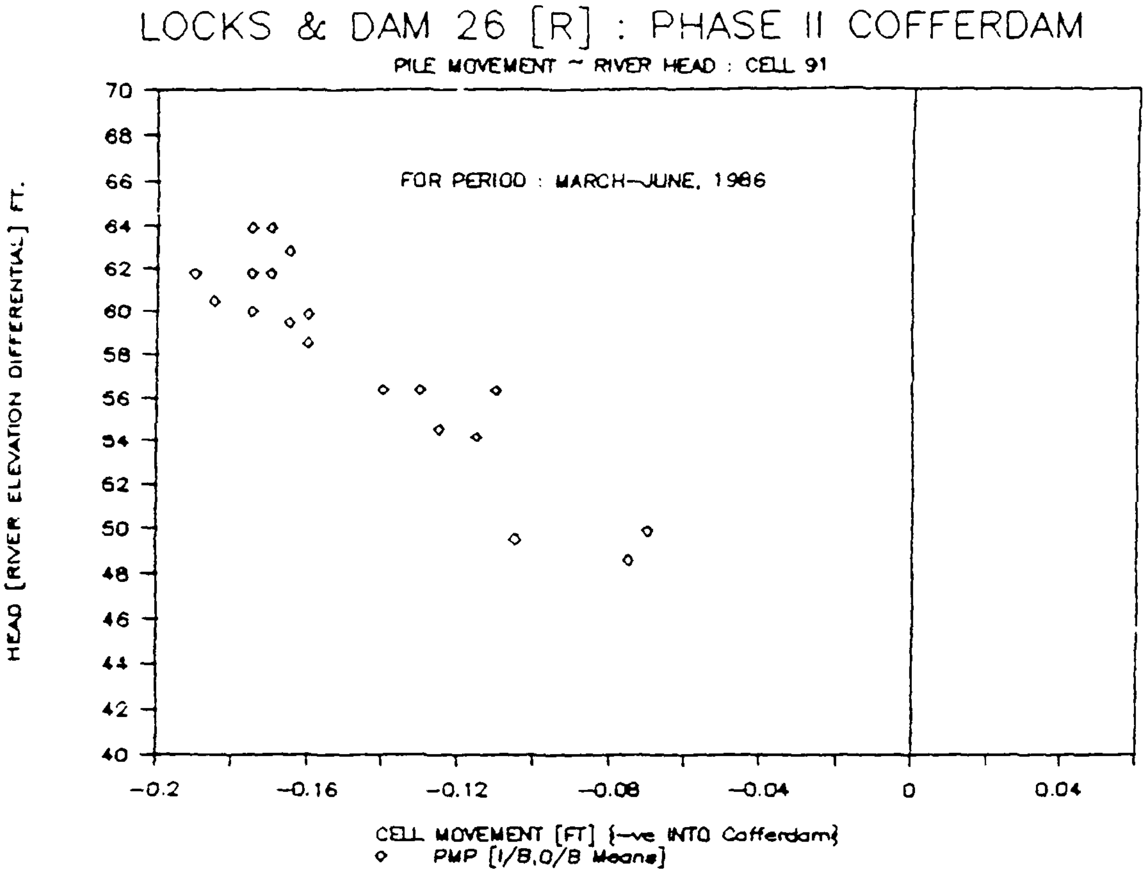


FIG 8.1 PILE MOVEMENT VS RIVER HEAD

CELL 91

MARCH-JUNE 1986

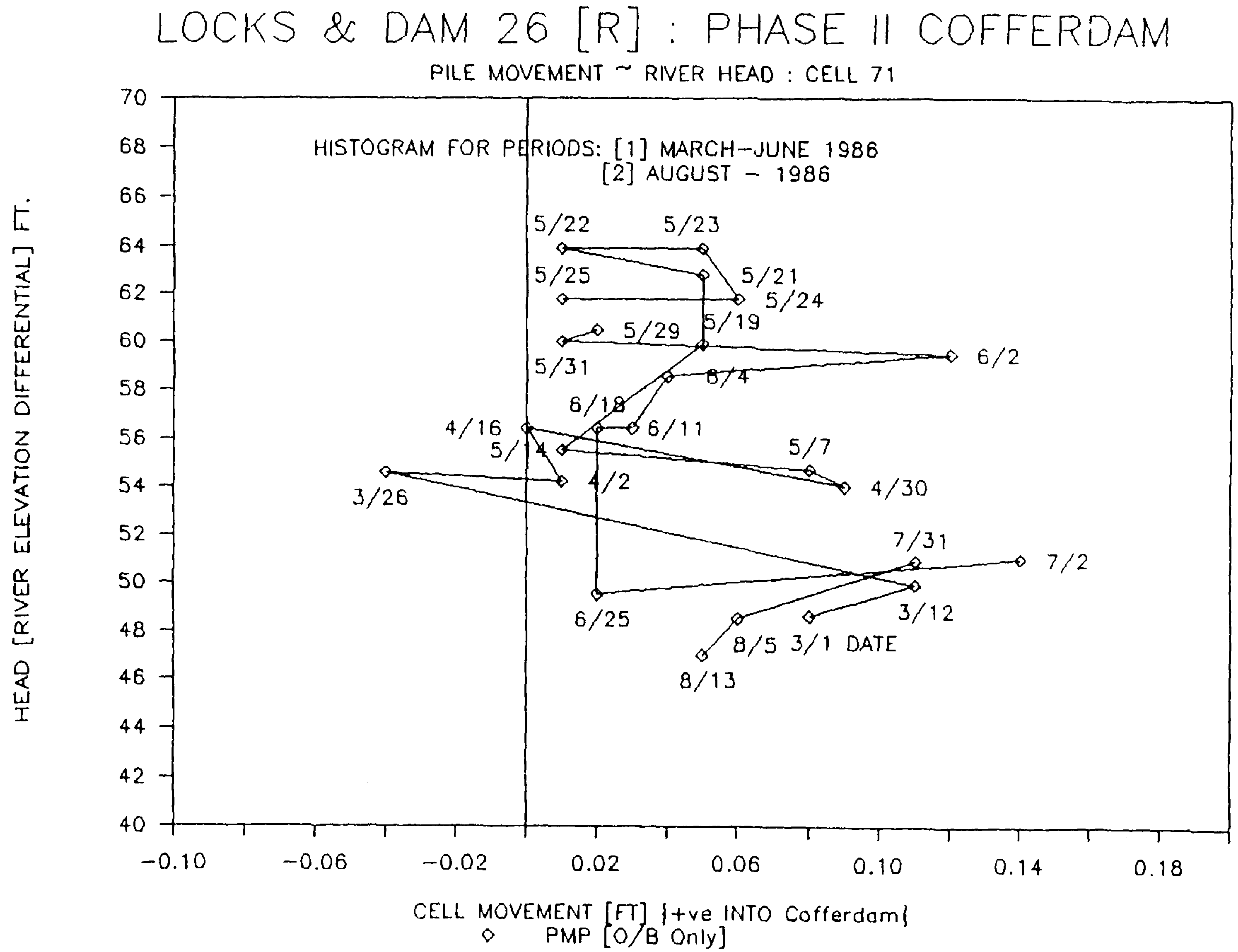


FIG 8.2 PILE MOVEMENT VS RIVER HEAD

CELL 71 MARCH–JUNE & AUGUST 1986

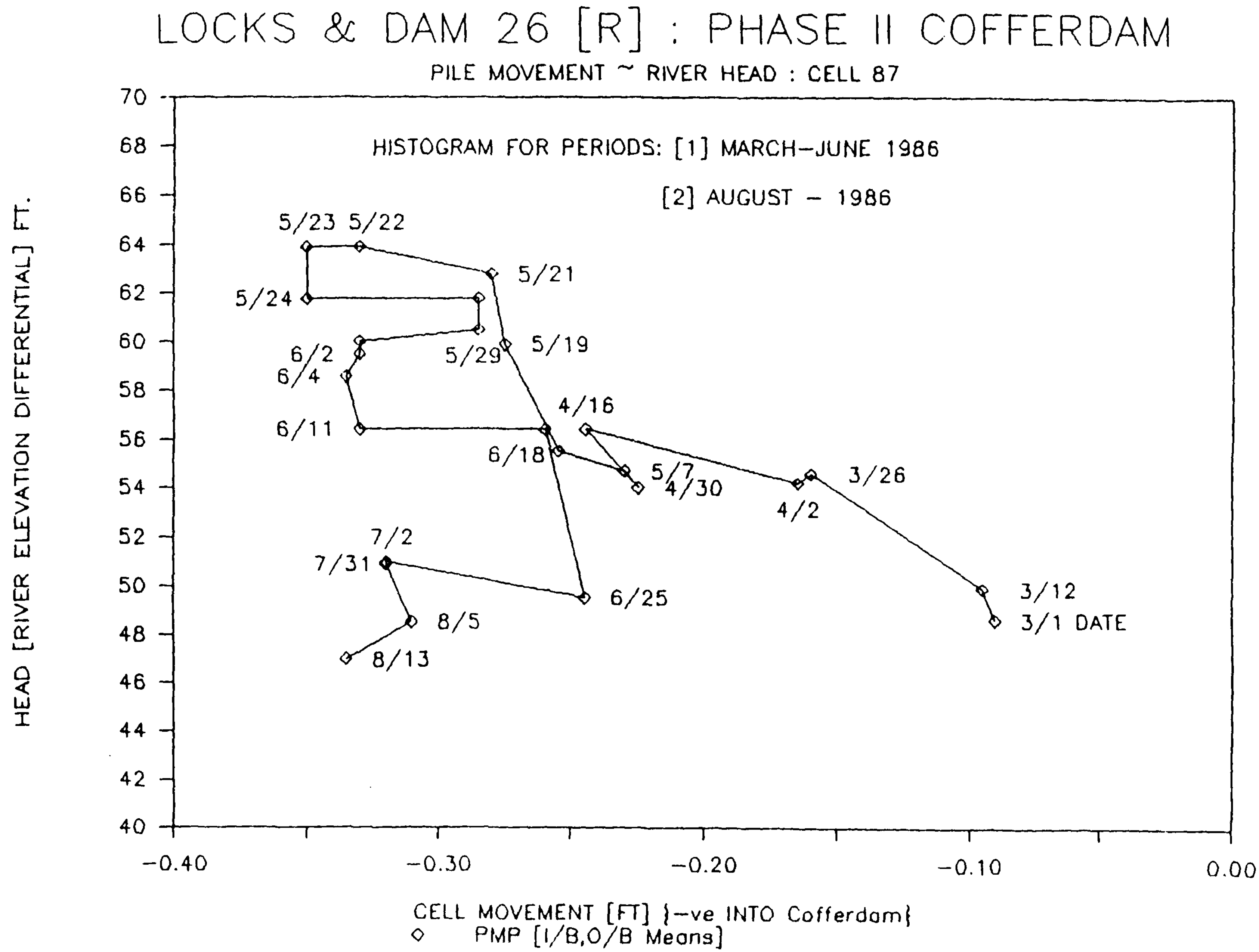


FIG 8.3 PILE MOVEMENT VS RIVER HEAD

CELL 87 MARCH–JUNE & AUGUST 1986

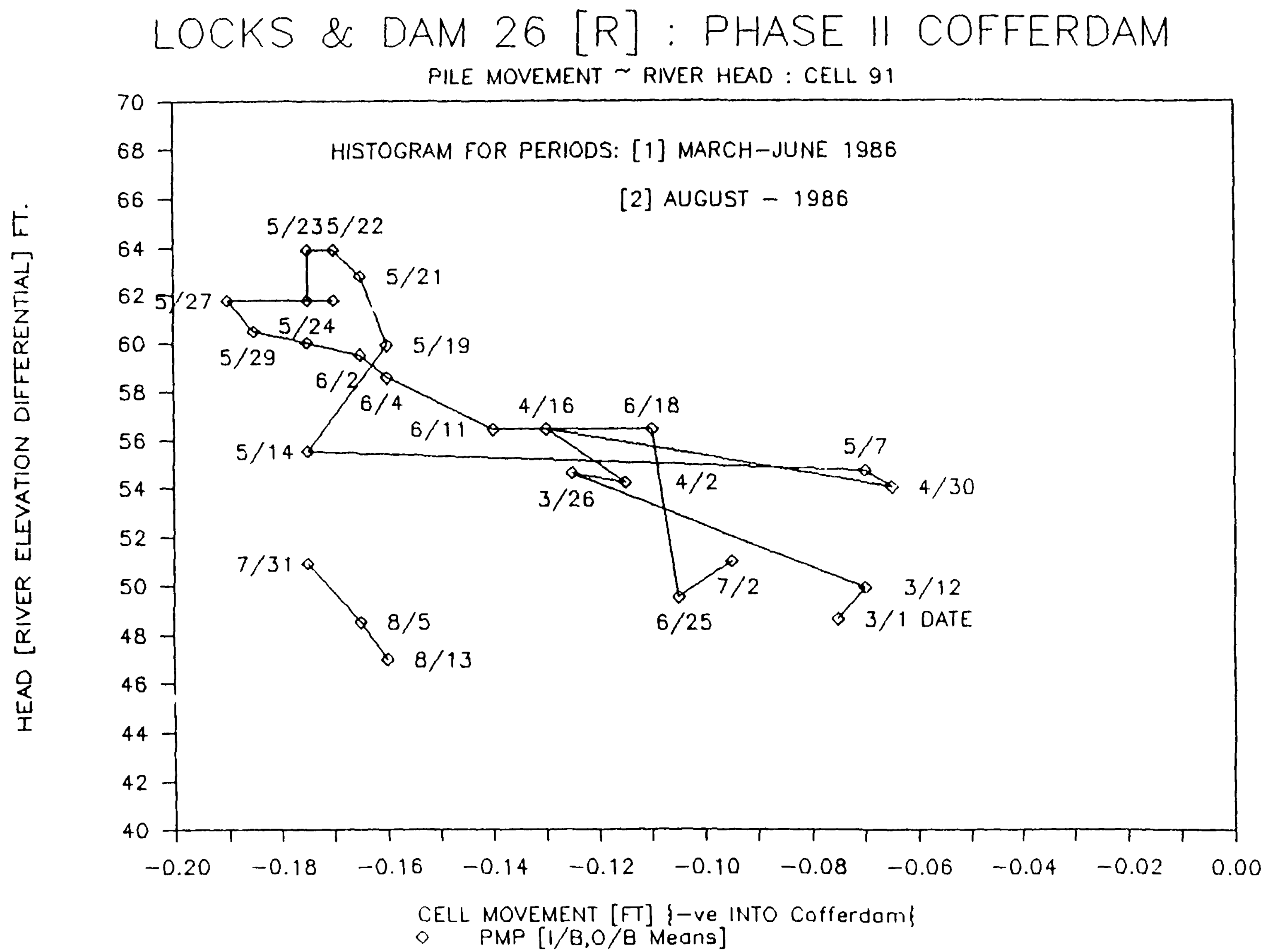
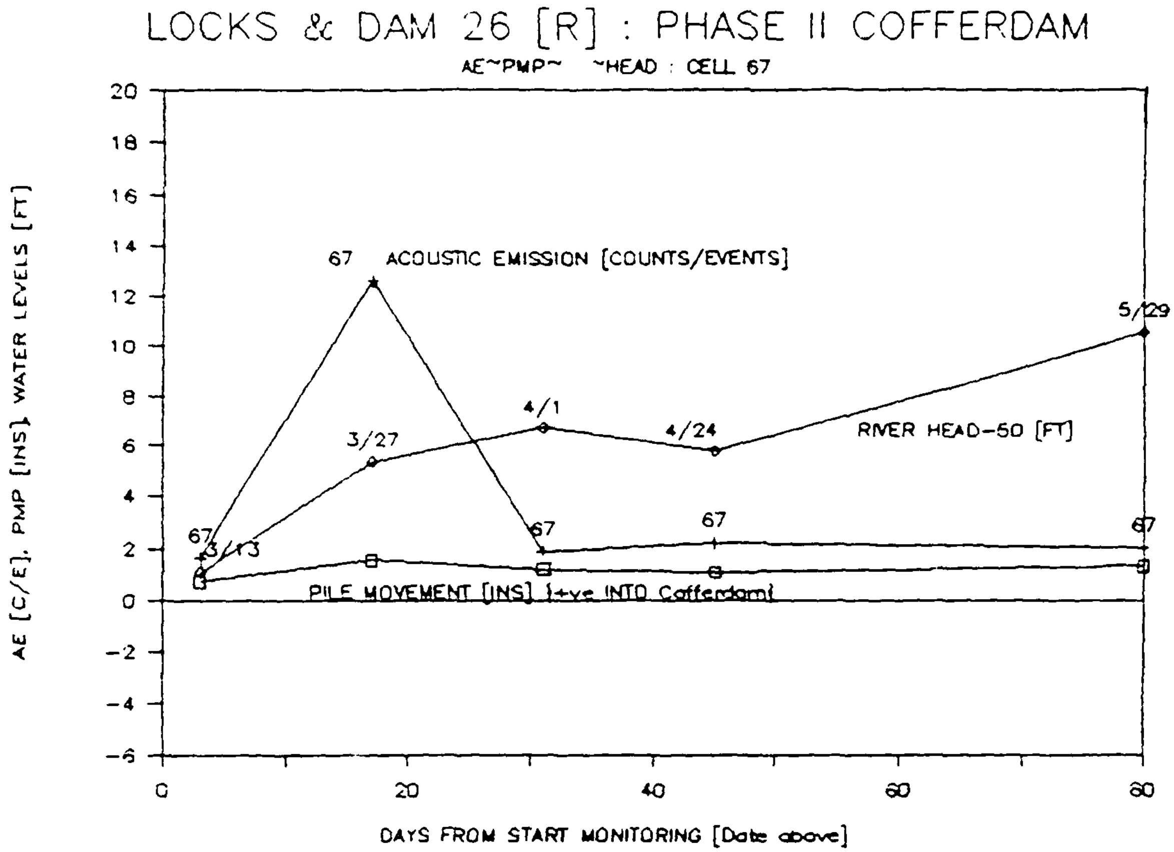


FIG 8.4 PILE MOVEMENT VS RIVER HEAD
CELL 91 MARCH–JUNE & AUGUST 1986



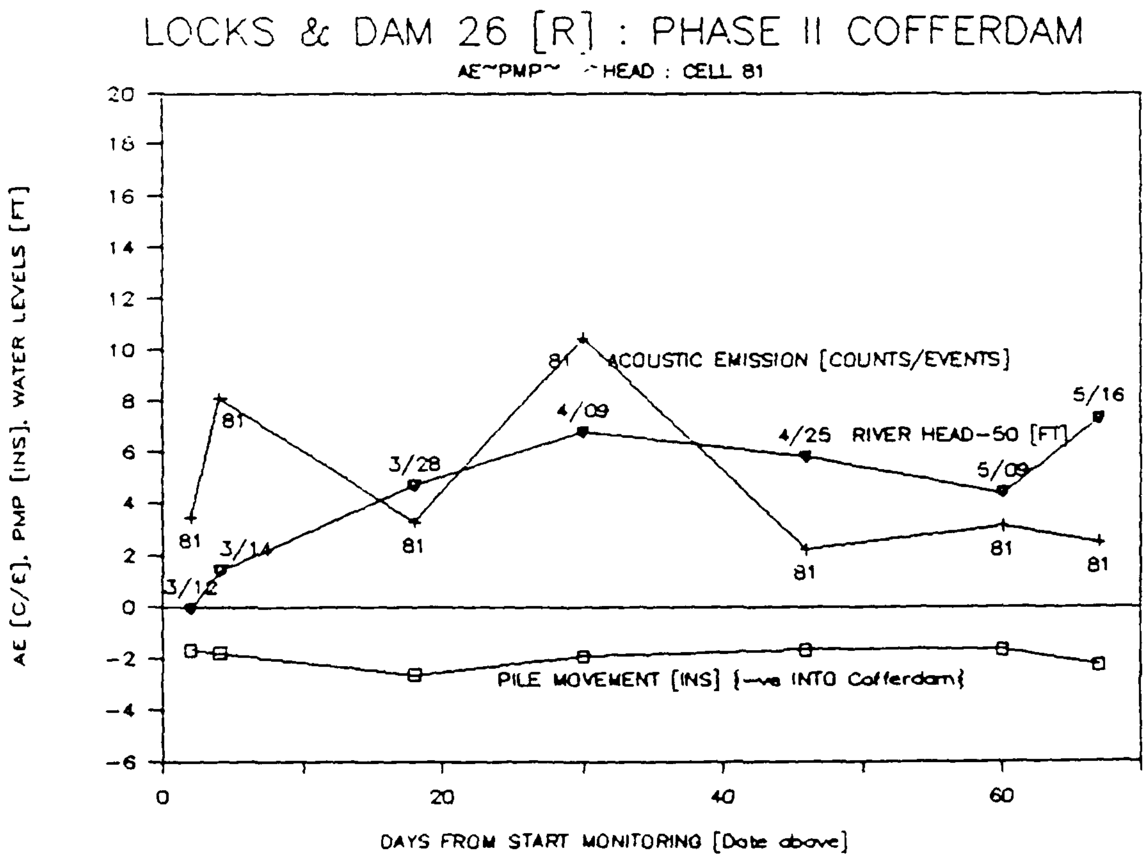
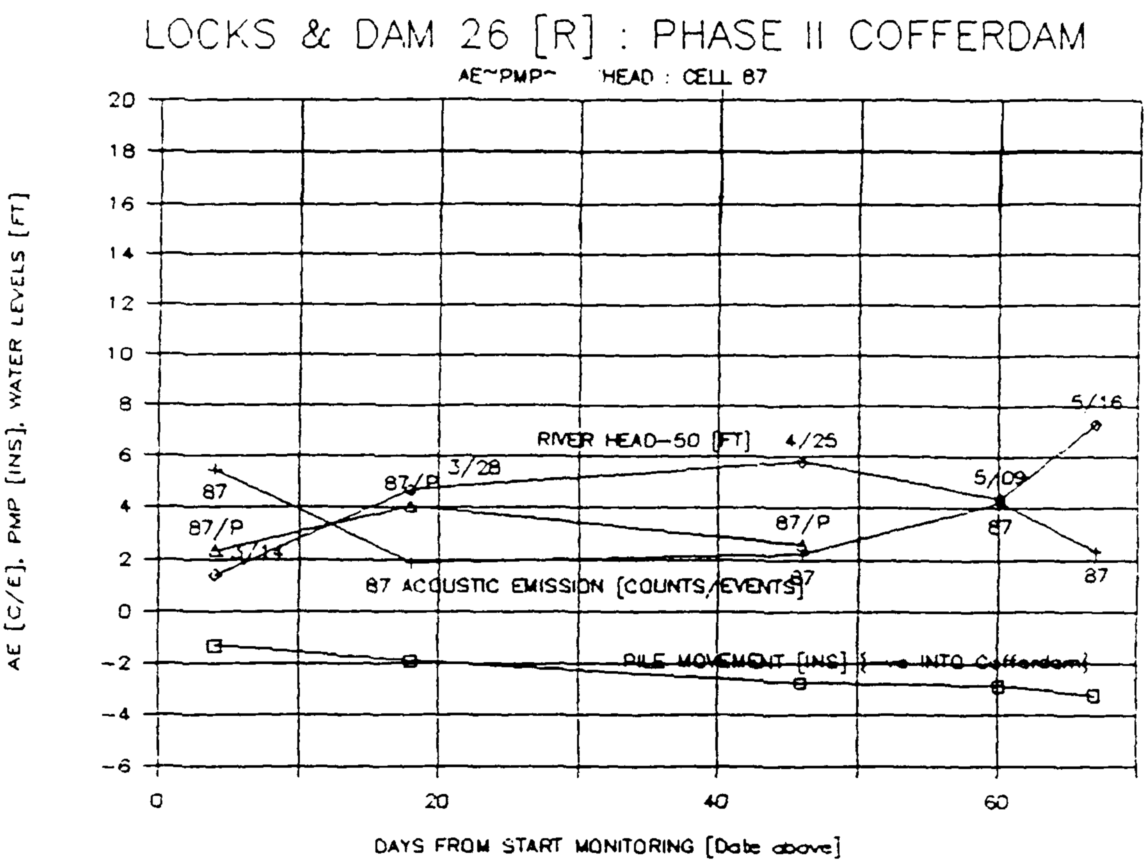


FIG 8.5 AE ACTIVITY, PILE MOVEMENT POINT DATA & RIVER HEAD
CELLS 67 & 81 MARCH-MAY 1986



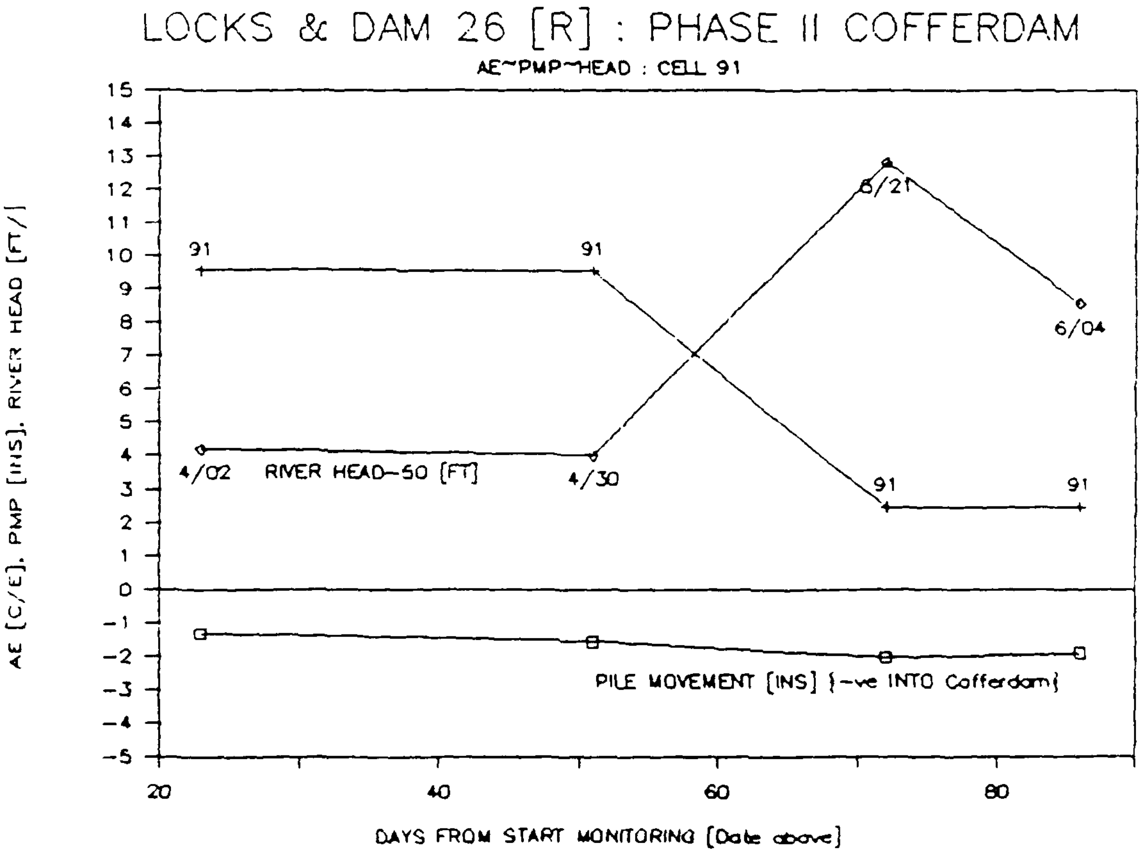


FIG 8.6 AE ACTIVITY, PILE MOVEMENT POINT DATA & RIVER HEAD
CELLS 87 & 91 MARCH-MAY 1986

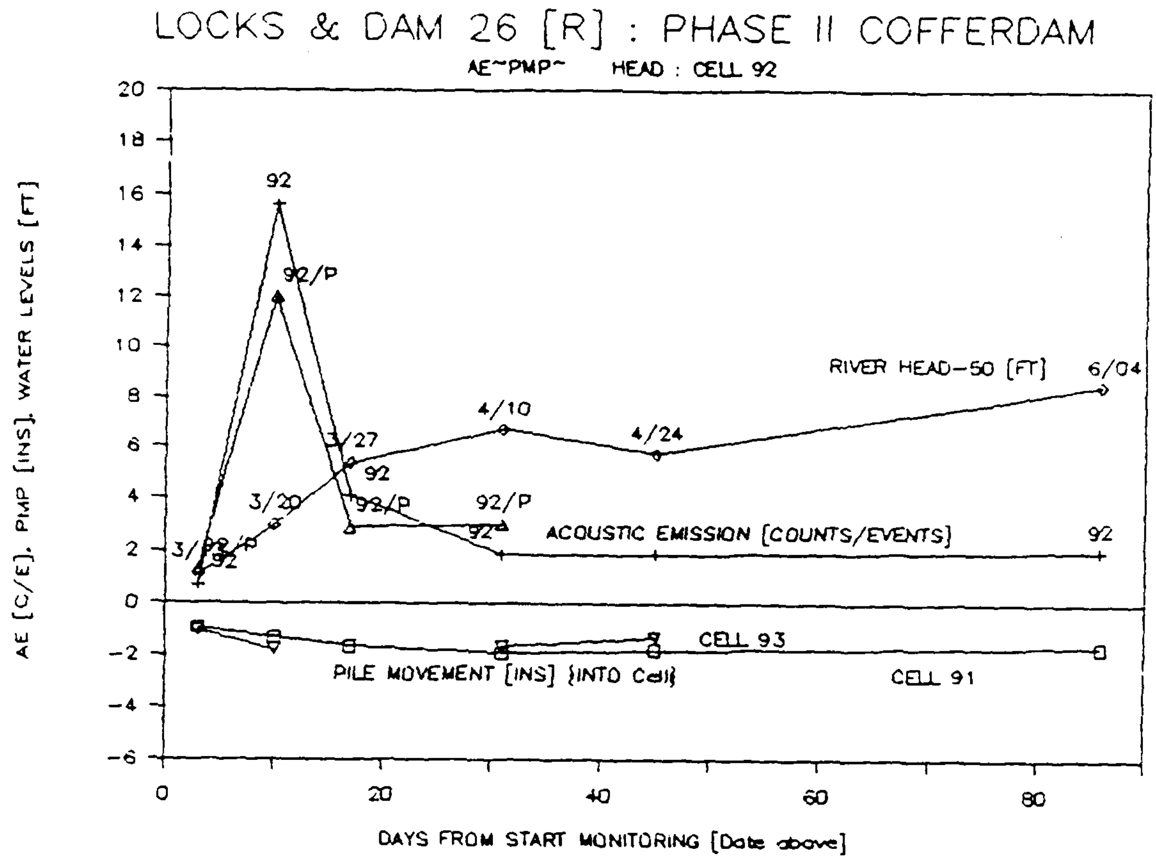


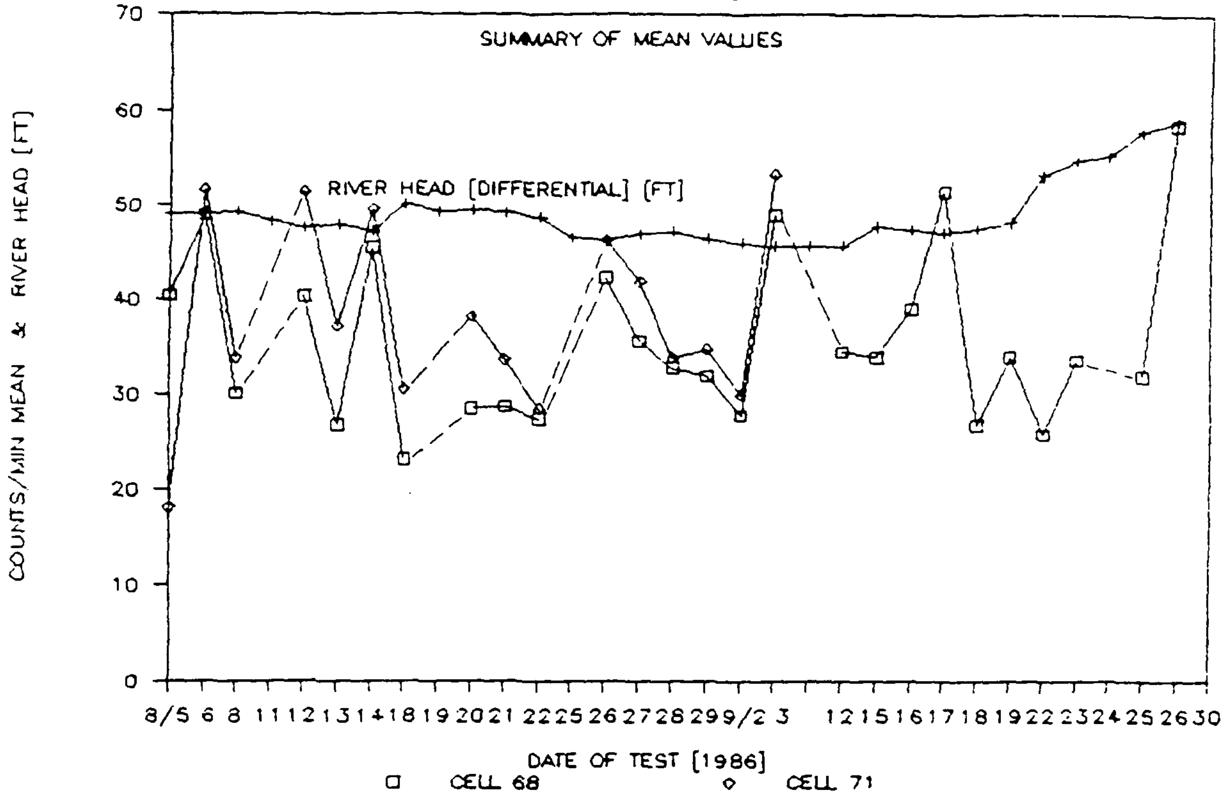
FIG 8.7 AE ACTIVITY, PILE MOVEMENT POINT DATA & RIVER HEAD CELL 92 MARCH-MAY 1986

FIG 8.8 AE ACTIVITY & RIVER HEAD

CELLS 68, 71, 80 & 87 AUGUST-SEPTEMBER 1986

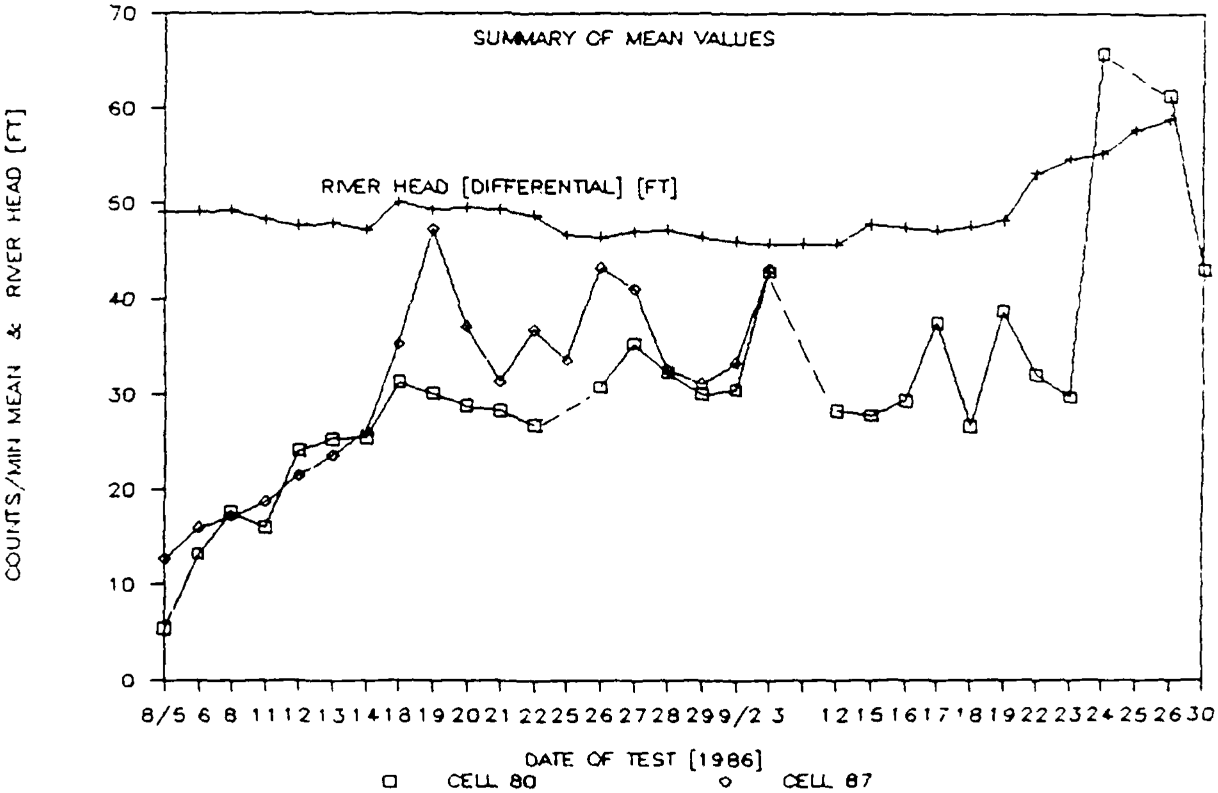
LOCKS & DAM 26 [R] : PHASE II COFFERDAM

SEMI-CONTINUOUS MONITORING ~ CELLS 68 & 71



LOCKS & DAM 26 [R] : PHASE II COFFERDAM

SEMI-CONTINUOUS MONITORING ~ CELLS 80 & 87



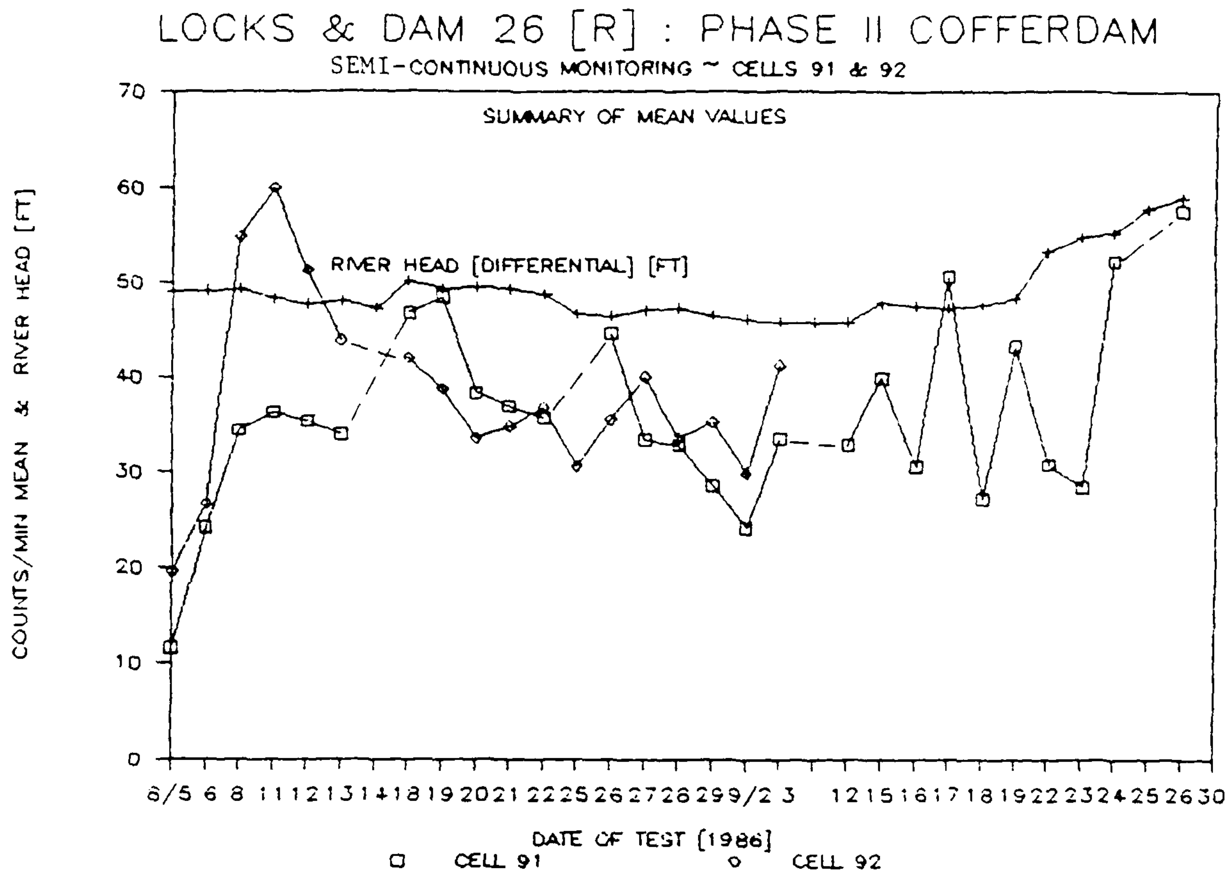


FIG 8.9 AE ACTIVITY & RIVER HEAD

CELLS 91 & 92 AUGUST-SEPTEMBER 1986

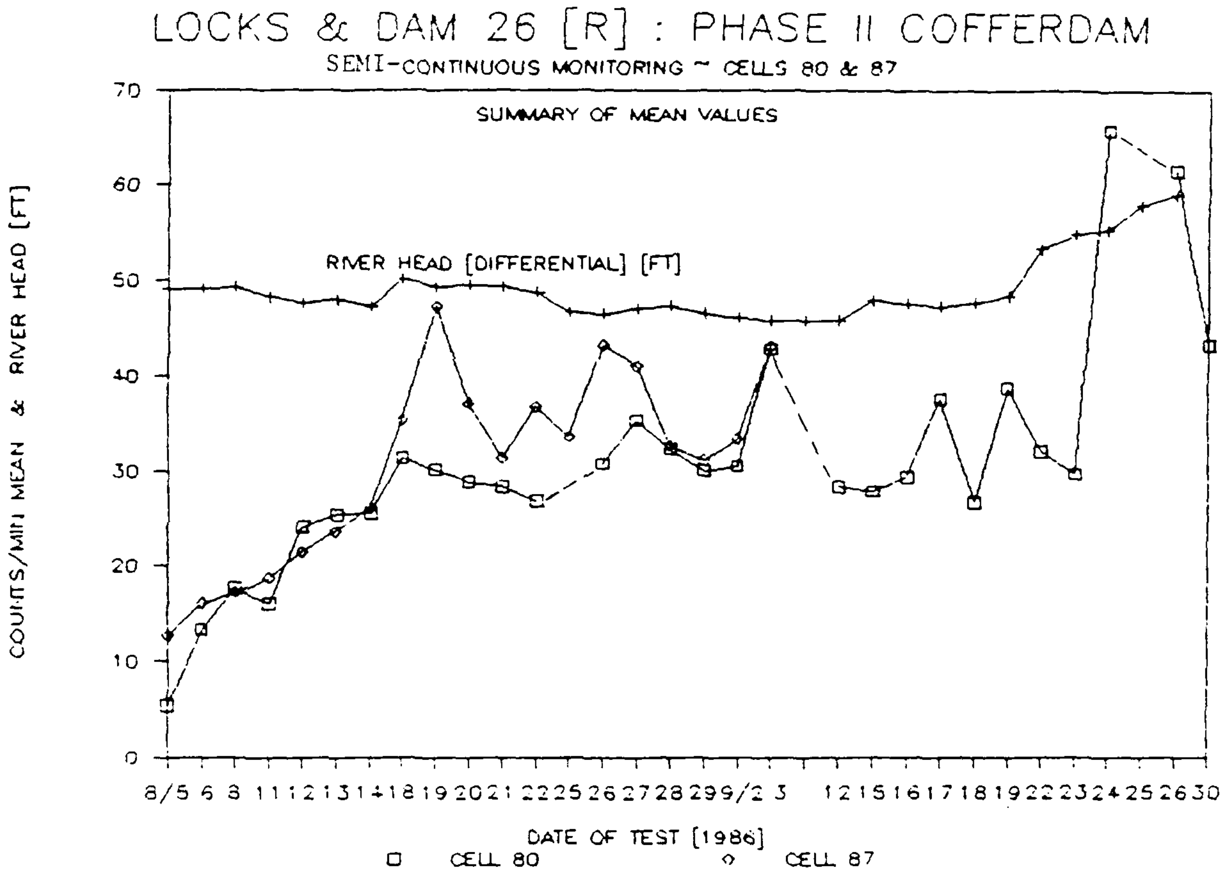
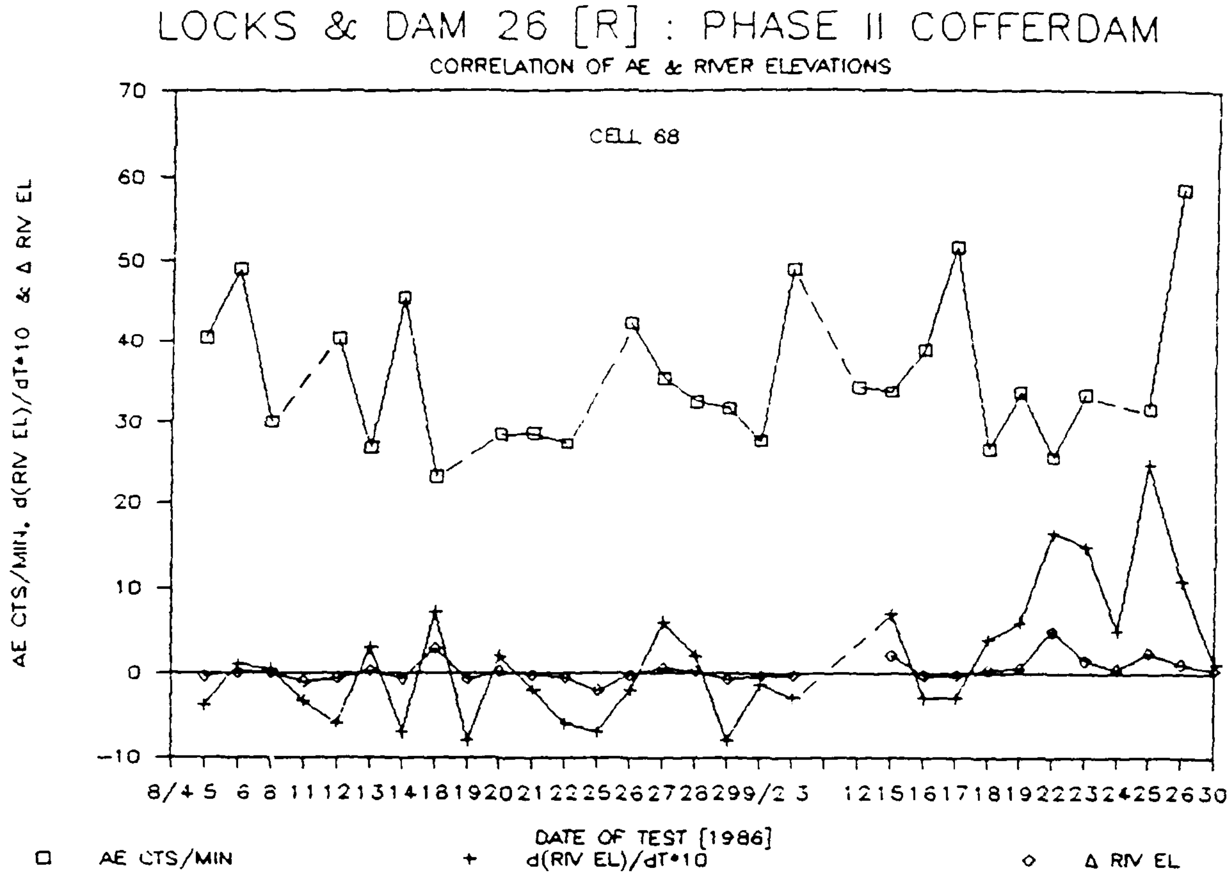


FIG 8.10 AE ACTIVITY & RIVER HEAD

CELLS 80 & 87 AUGUST-SEPTEMBER 1986



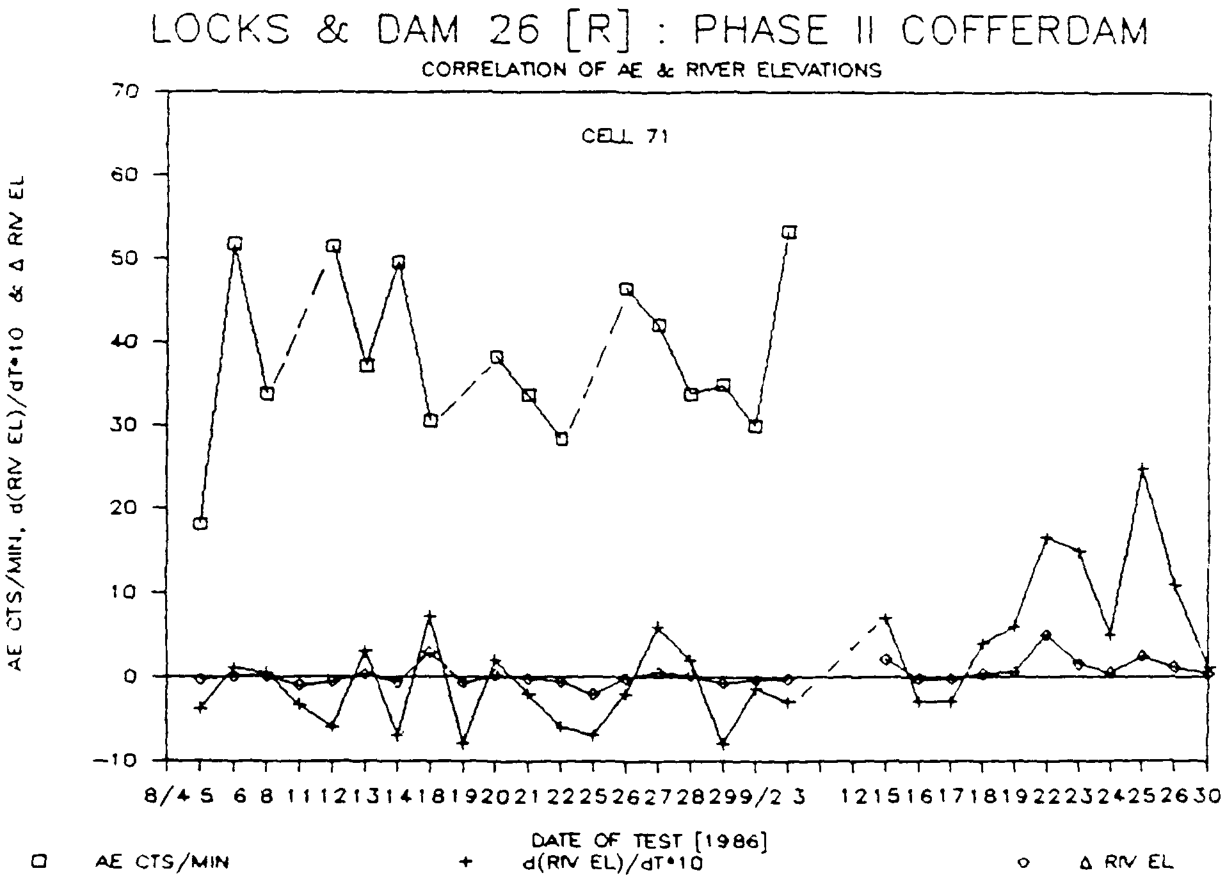
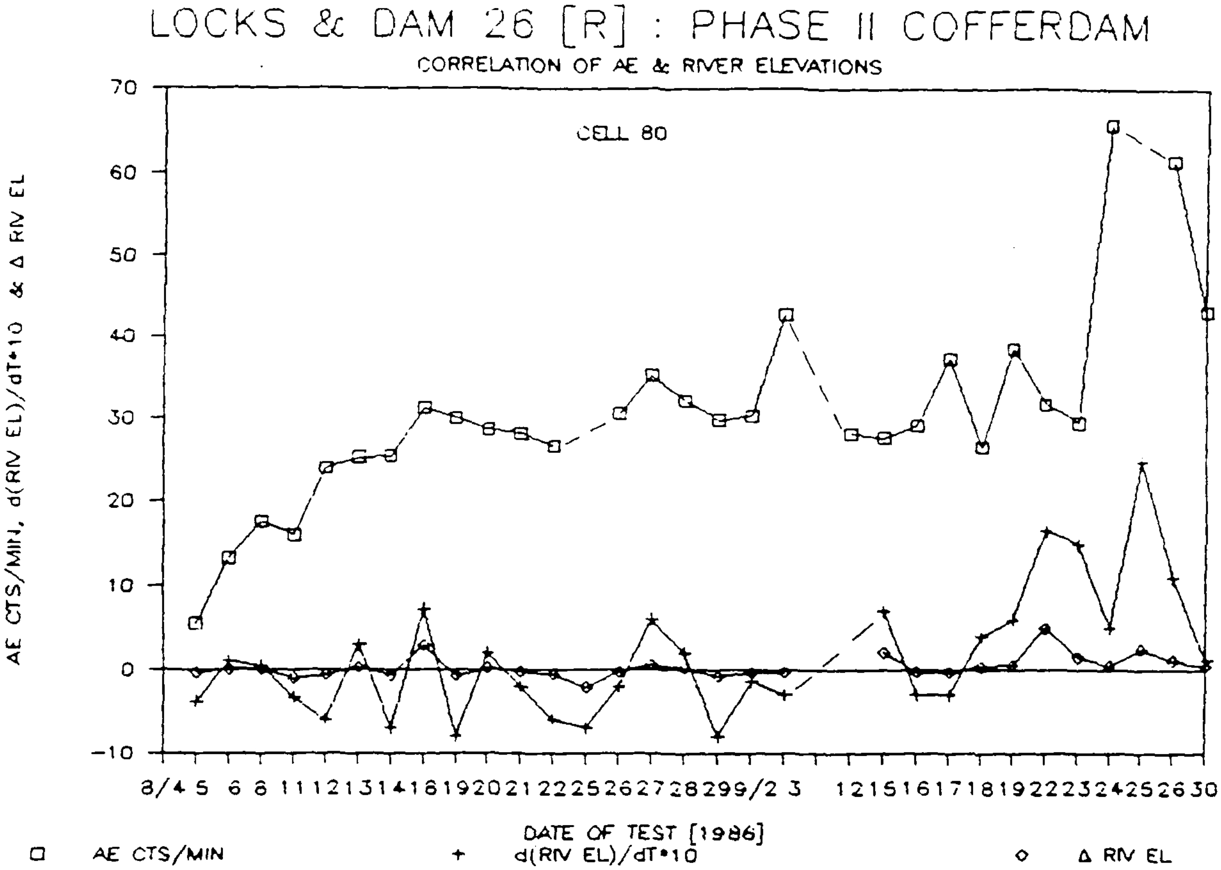
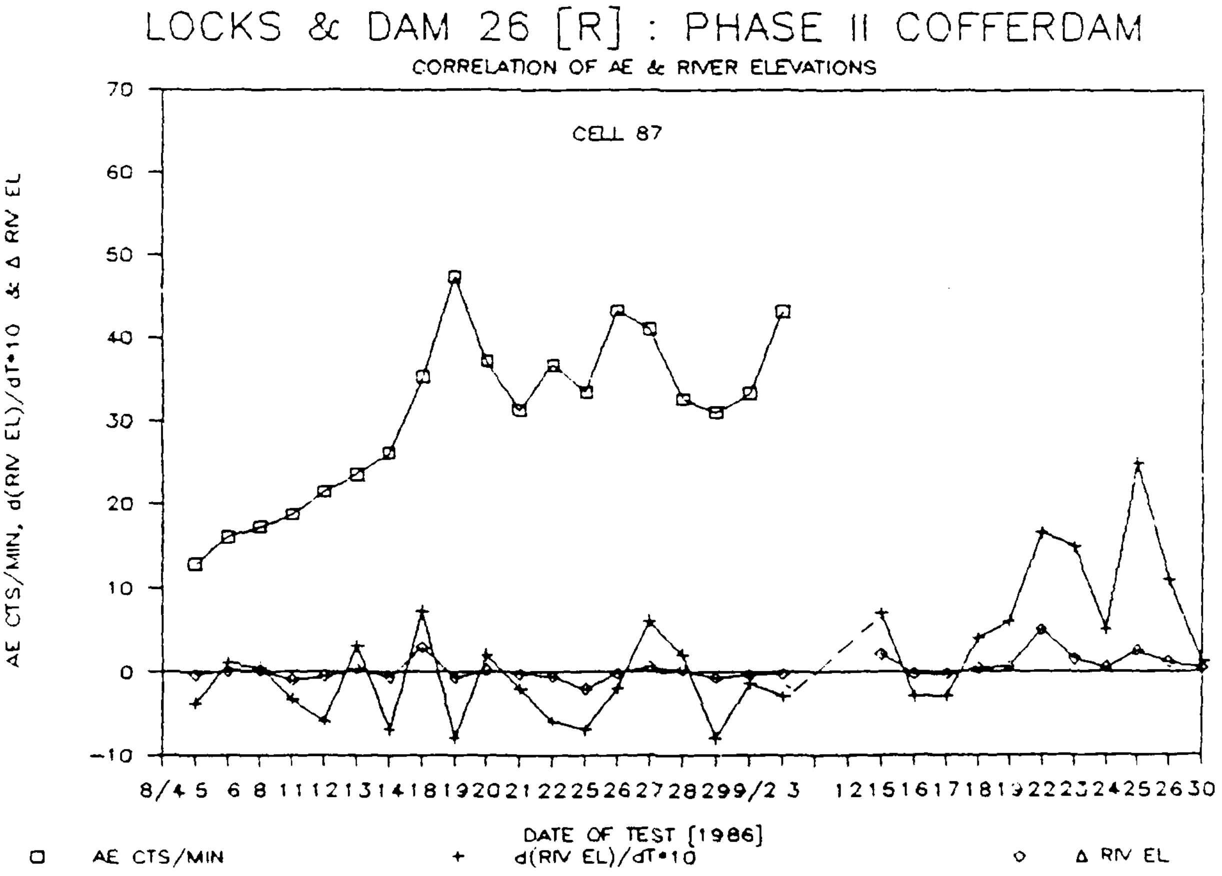


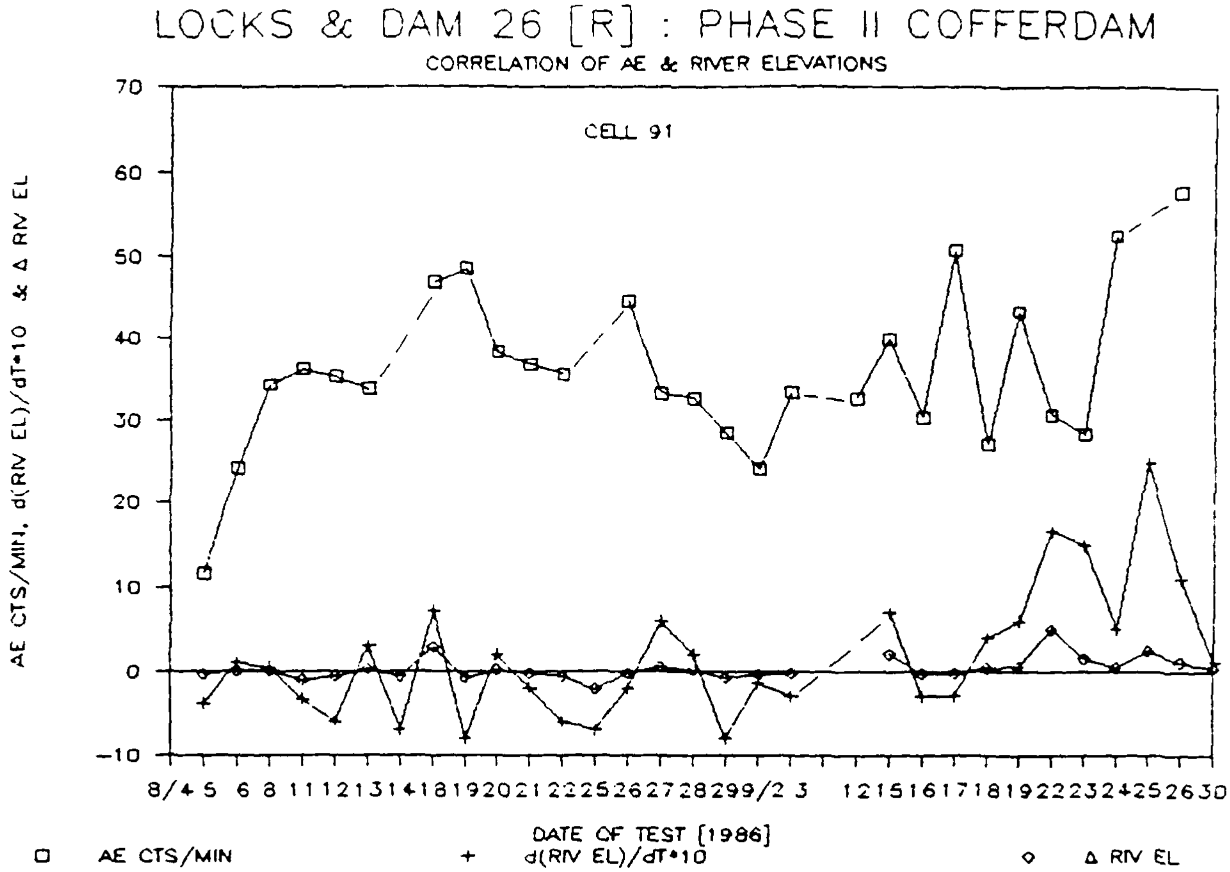
FIG 8.11 AE ACTIVITY, △ RIVER HEAD, RATE OF △ RIVER HEAD
CELLS 68 & 71 AUGUST-SEPTEMBER 1986

FIG 8.12 AE ACTIVITY, Δ RIVER HEAD, RATE OF Δ RIVER HEAD

CELLS 80 & 87 AUGUST-SEPTEMBER 1986







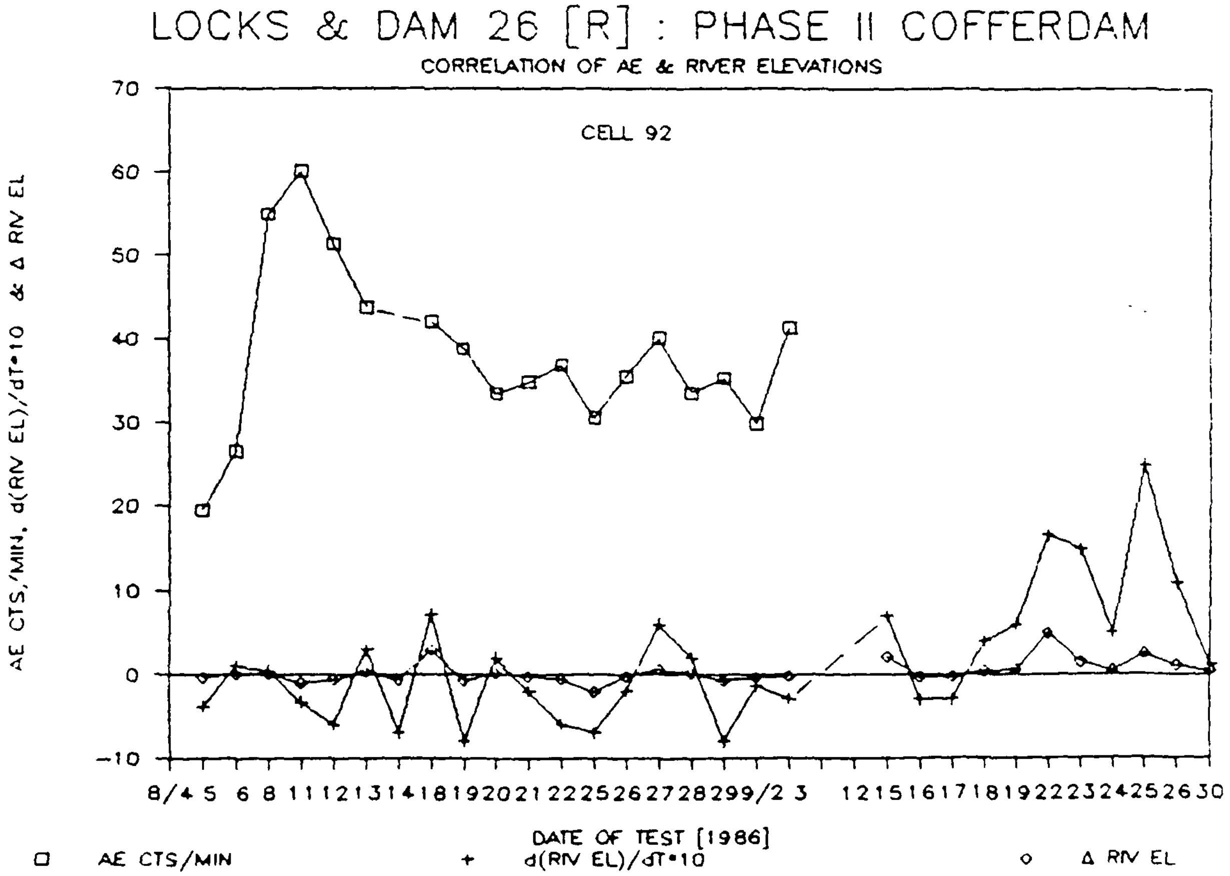


FIG 8.13 AE ACTIVITY, Δ RIVER HEAD, RATE OF Δ RIVER HEAD

CELLS 91 & 92 AUGUST-SEPTEMBER 1986

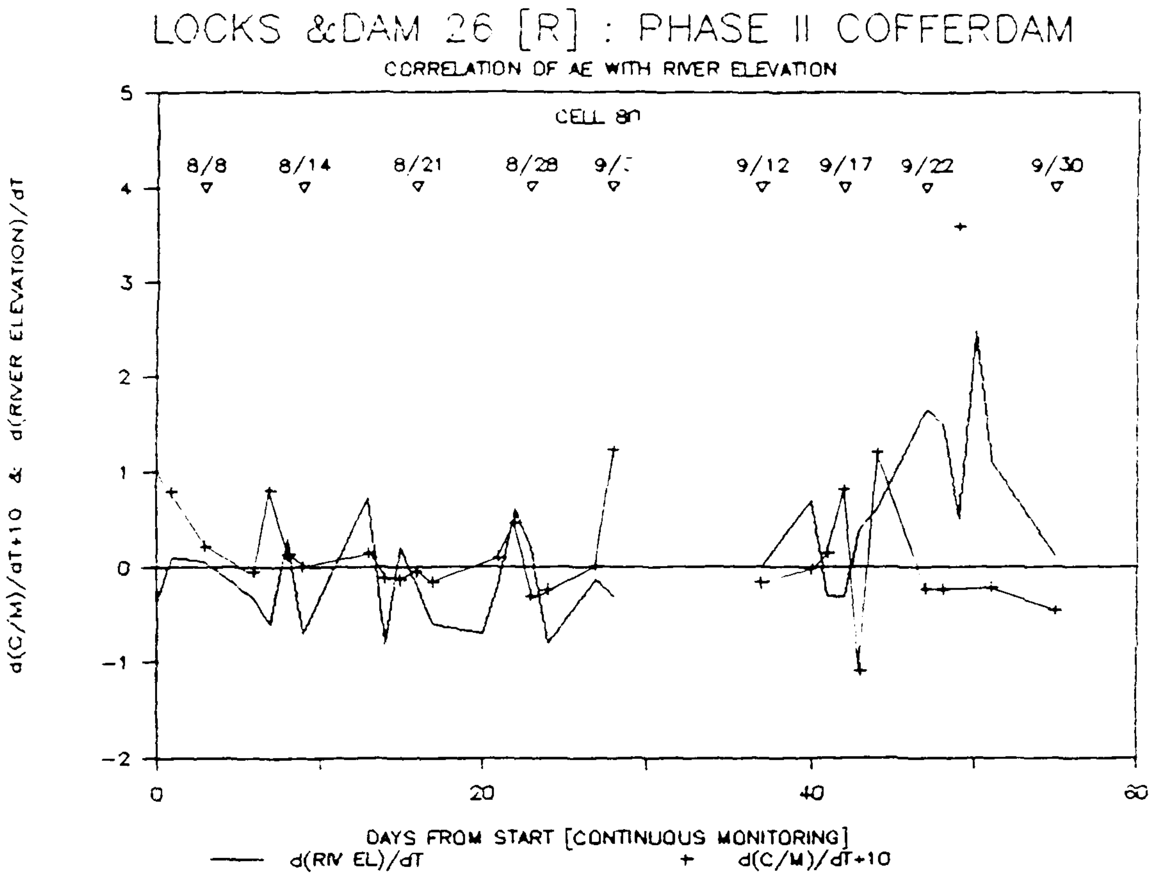


FIG 8.14 AE ACTIVITY, △ RIVER HEAD, RATE OF △ RIVER HEAD

CELL 80 AUGUST-SEPTEMBER 1986

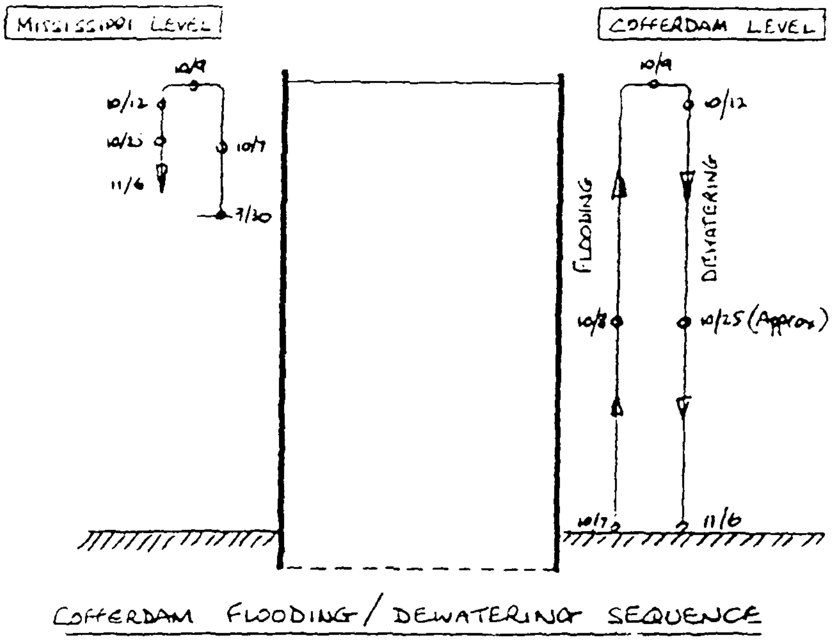


FIG 8.15 COFFERDAM FLOODING/DEWATERING SEQUENCE

SCHEMATIC

OCTOBER-NOVEMBER 1936

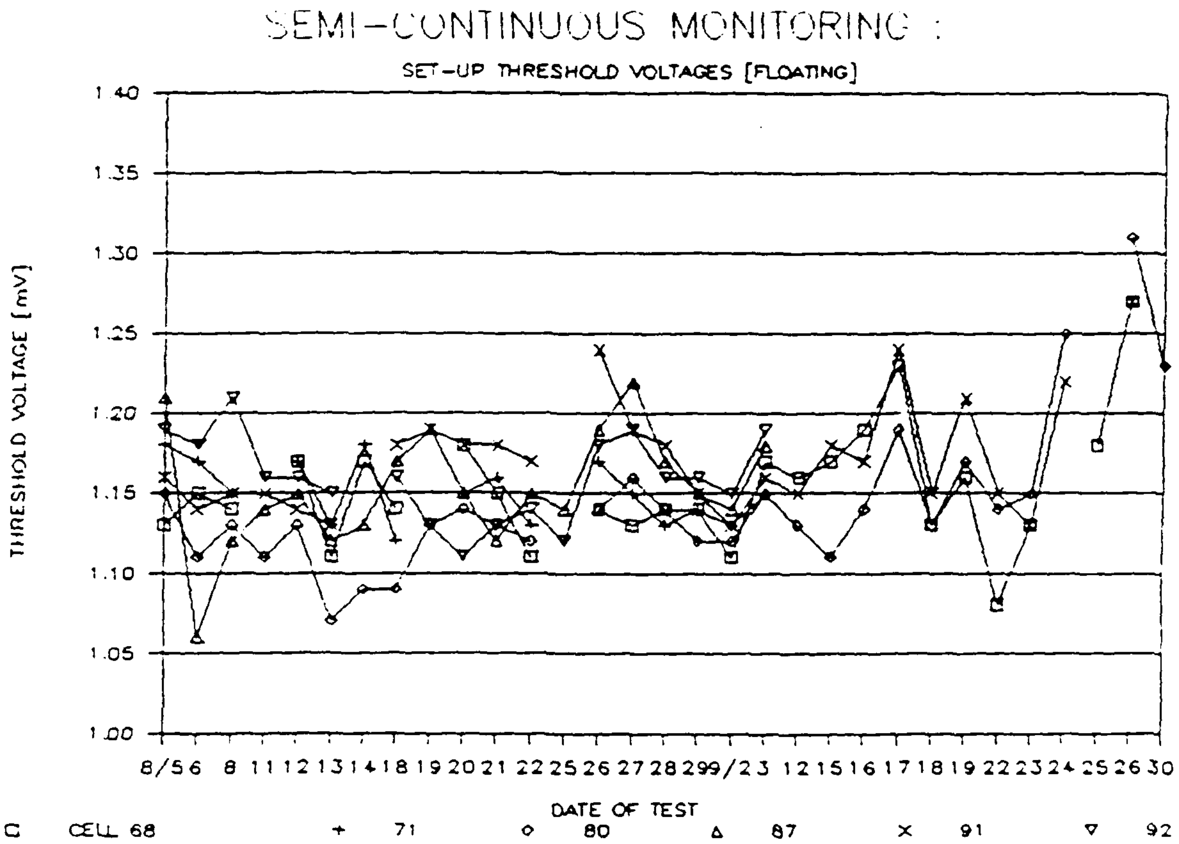


FIG 8.16 AET 204GR FLOATING THRESHOLD SET-UP VOLTAGE

AUGUST-SEPTEMBER 1986

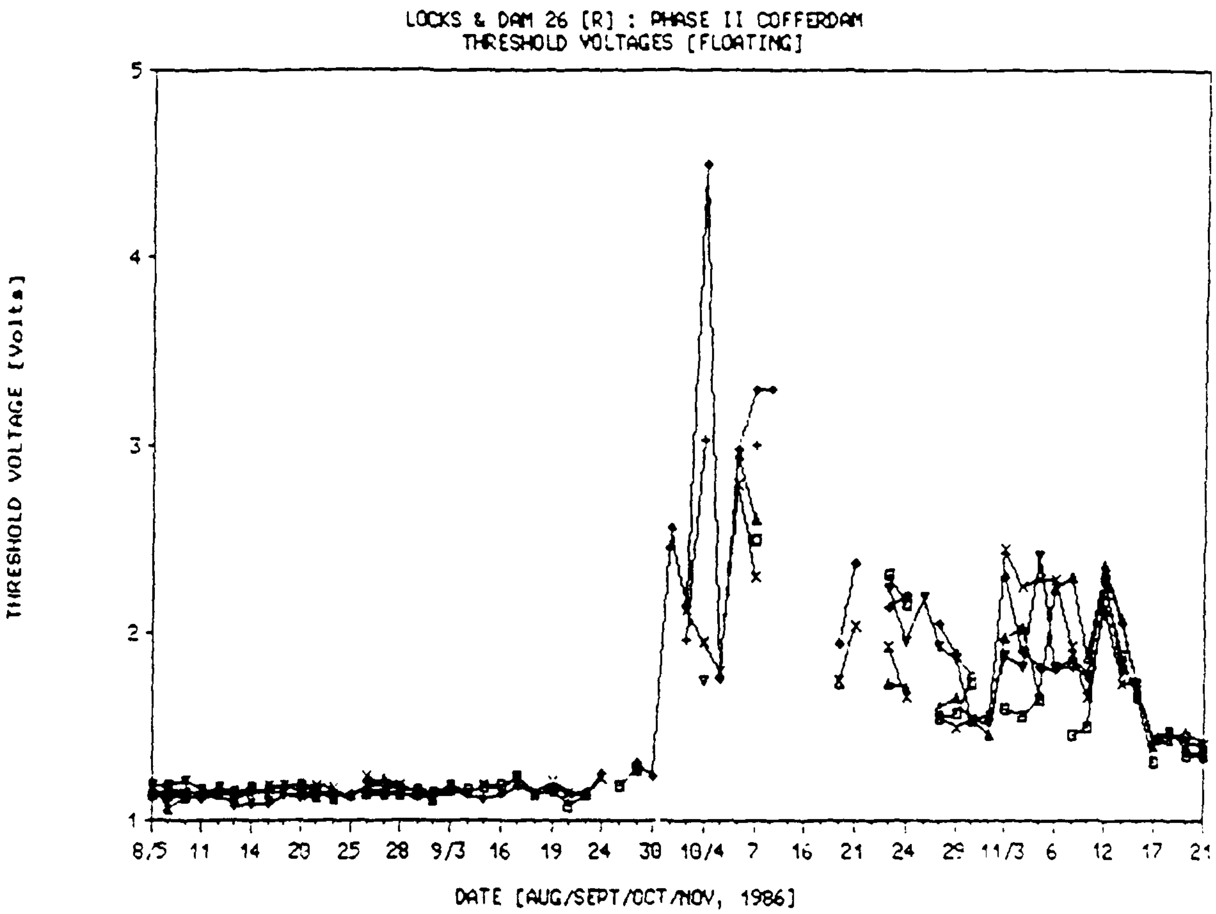


FIG 8.17 AET 204GR FLOATING THRESHOLD SET-UP VOLTAGE AUGUST-NOVEMBER 1986

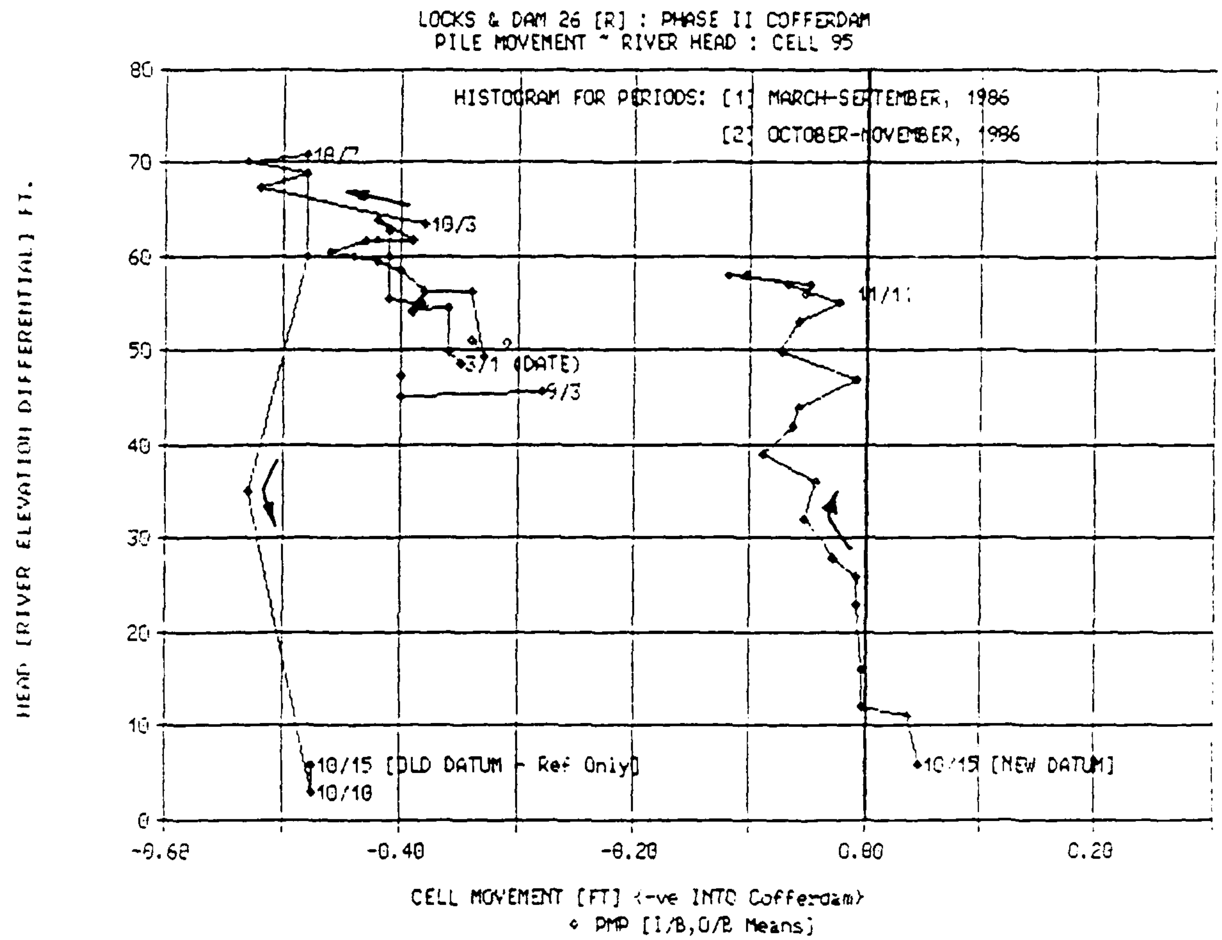


FIG 8.18 PILE MOVEMENT VS RIVER HEAD

CELL 95

MARCH-SEPTEMBER & OCTOBER-NOVEMBER 1986

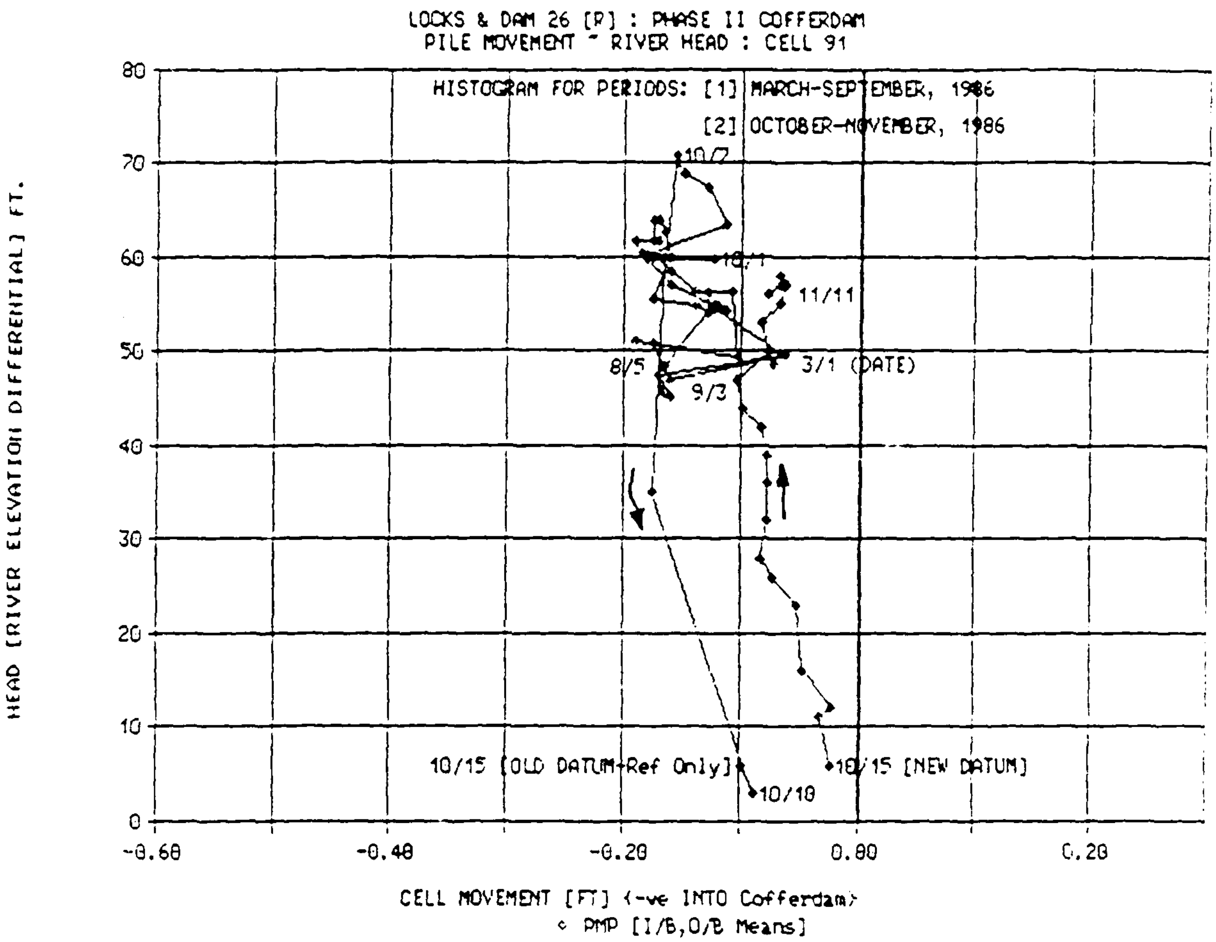


FIG 8.19 PILE MOVEMENT VS RIVER HEAD

CELL 91

MARCH-SEPTEMBER & OCTOBER-NOVEMBER 1986

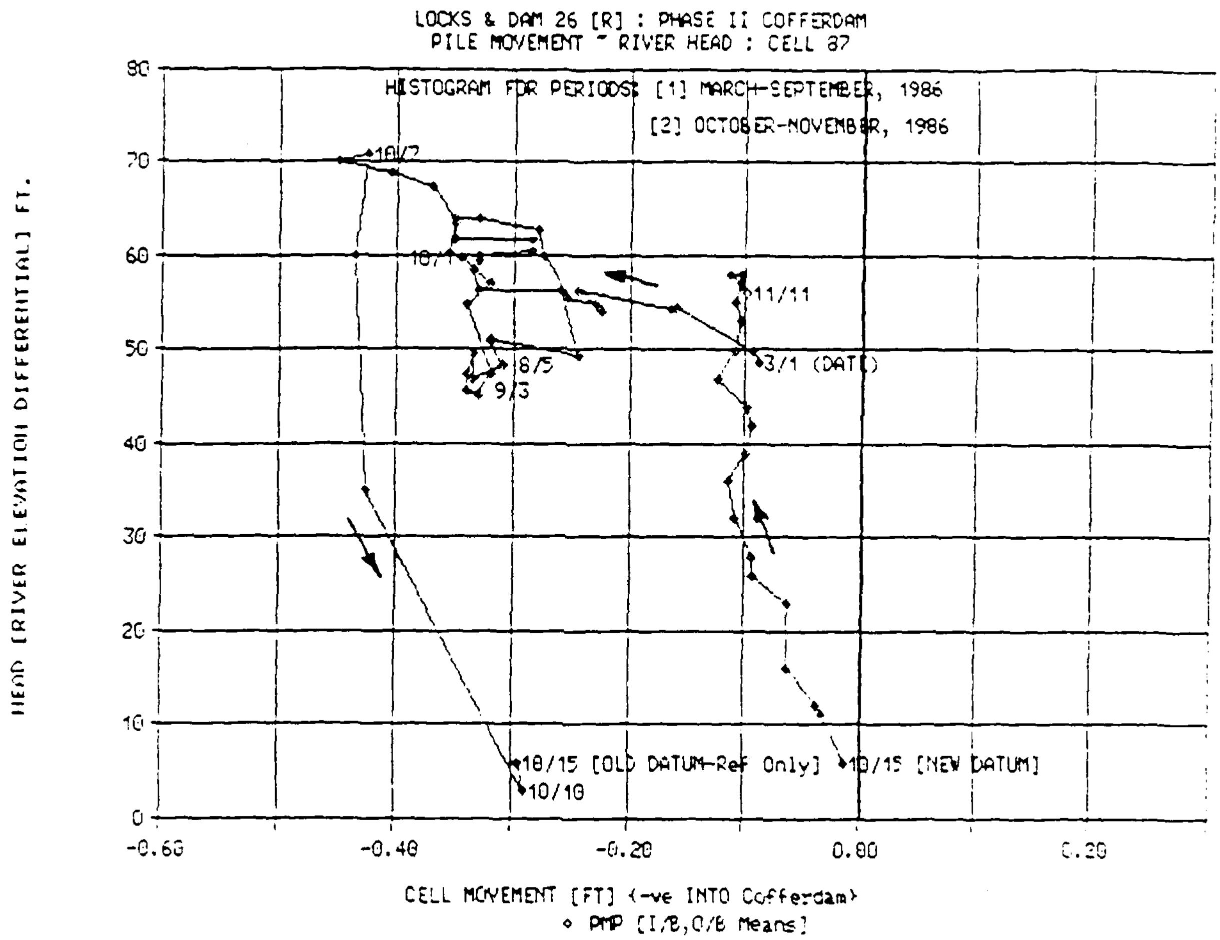


FIG 8.20 PILE MOVEMENT VS RIVER HEAD

CELL 87

MARCH-SEPTEMBER & OCTOBER-NOVEMBER 1986

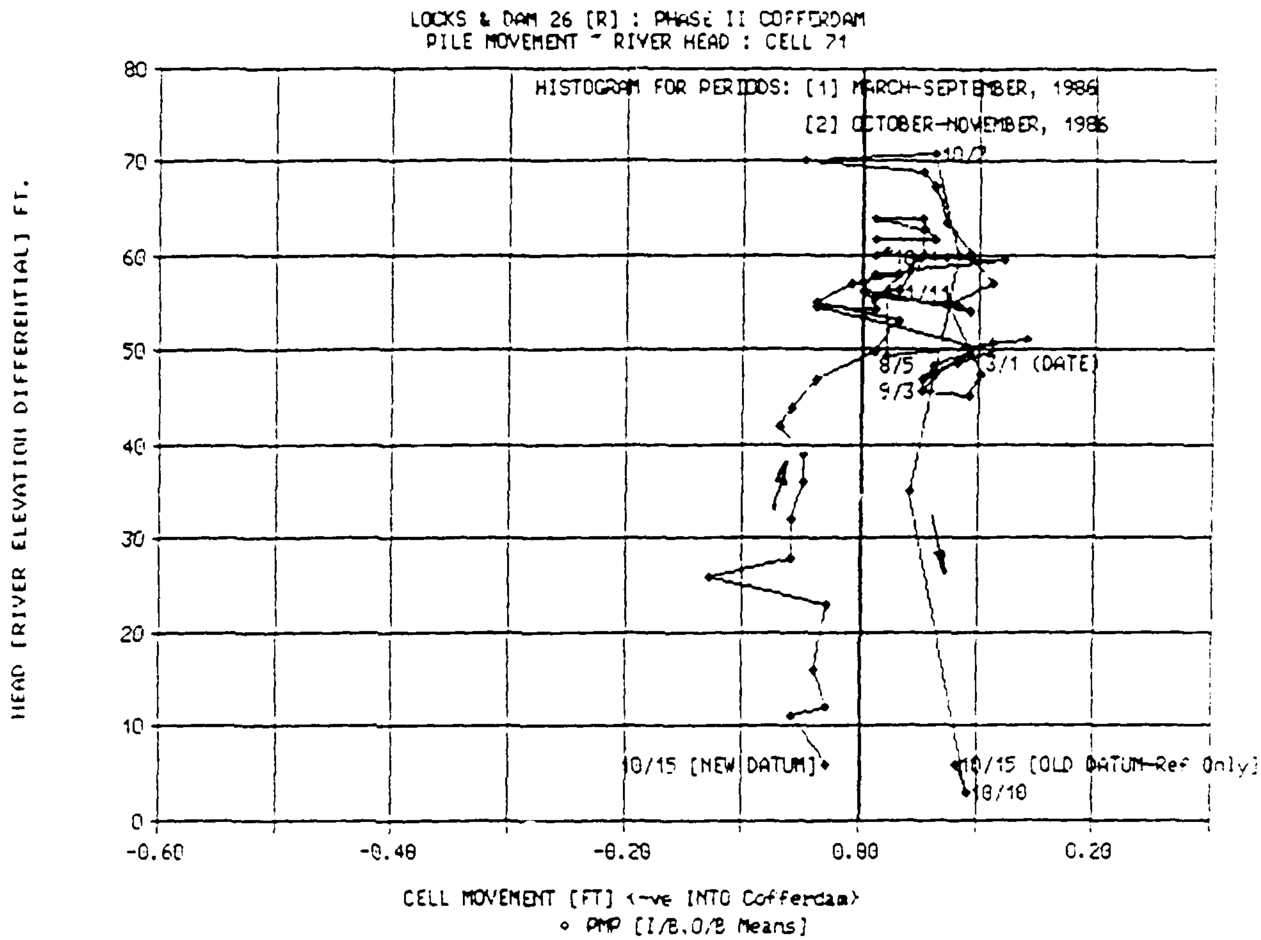


FIG 8.21 PILE MOVEMENT VS RIVER HEAD

CELL 71

MARCH-SEPTEMBER & OCTOBER-NOVEMBER 1986

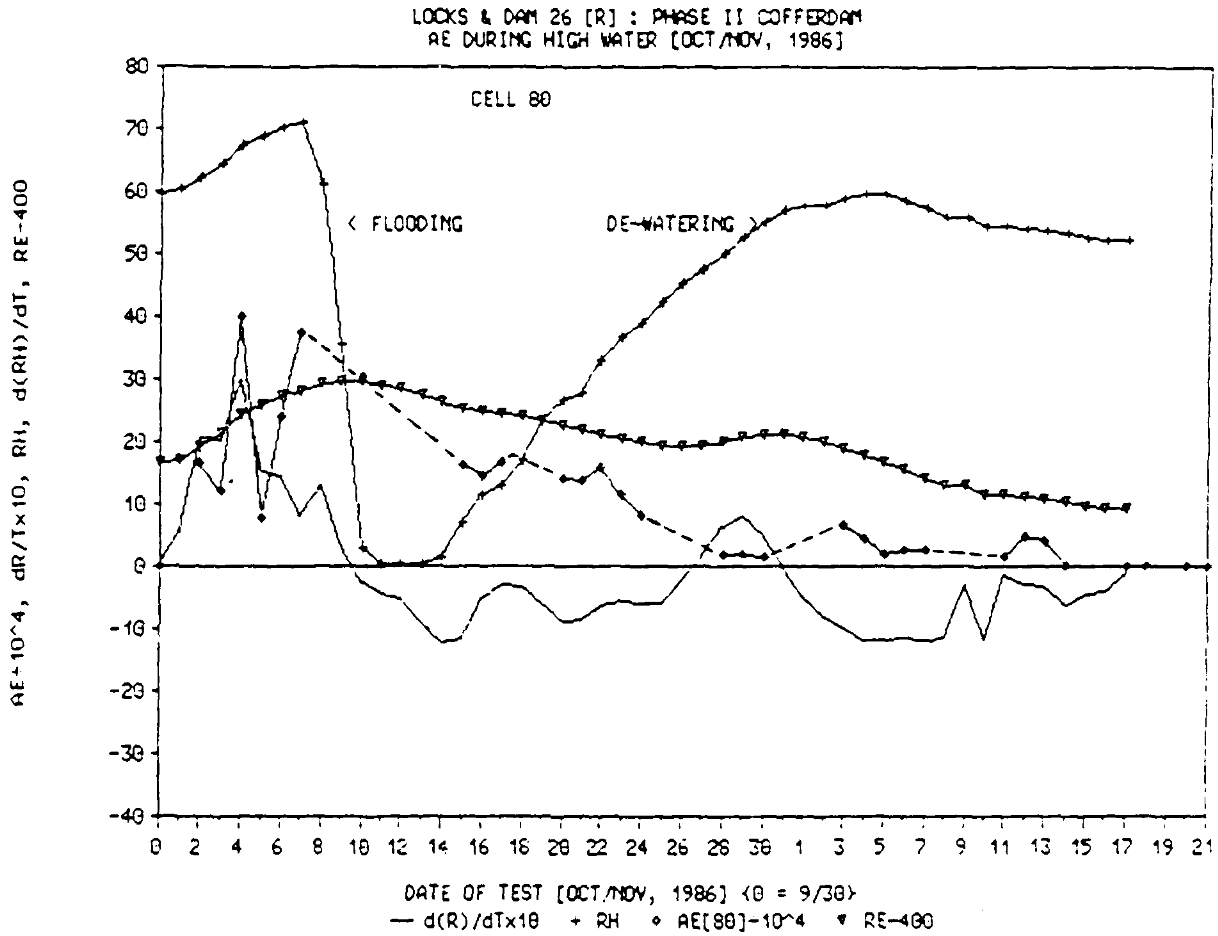


FIG 8.22 AE ACTIVITY RIVER ELEVATION RIVER HEAD, RATE OF CHANGE IN RIVER ELEVATION

CELL 80

OCTOBER-NOVEMBER 1986

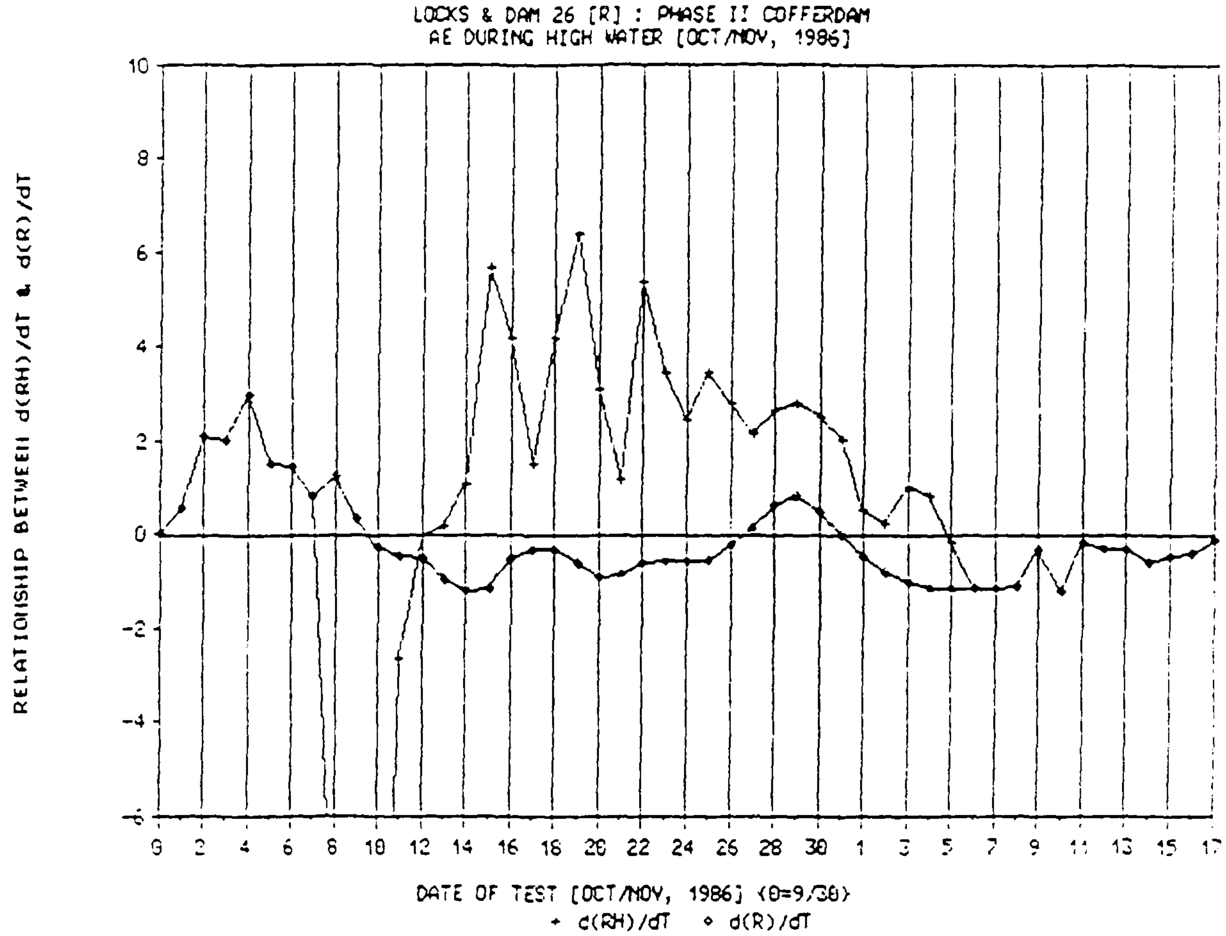


FIG 8.23 RATE OF CHANGE IN RIVER ELEVATION, RATE OF CHANGE IN RIVER HEAD

OCTOBER-NOVEMBER 1986

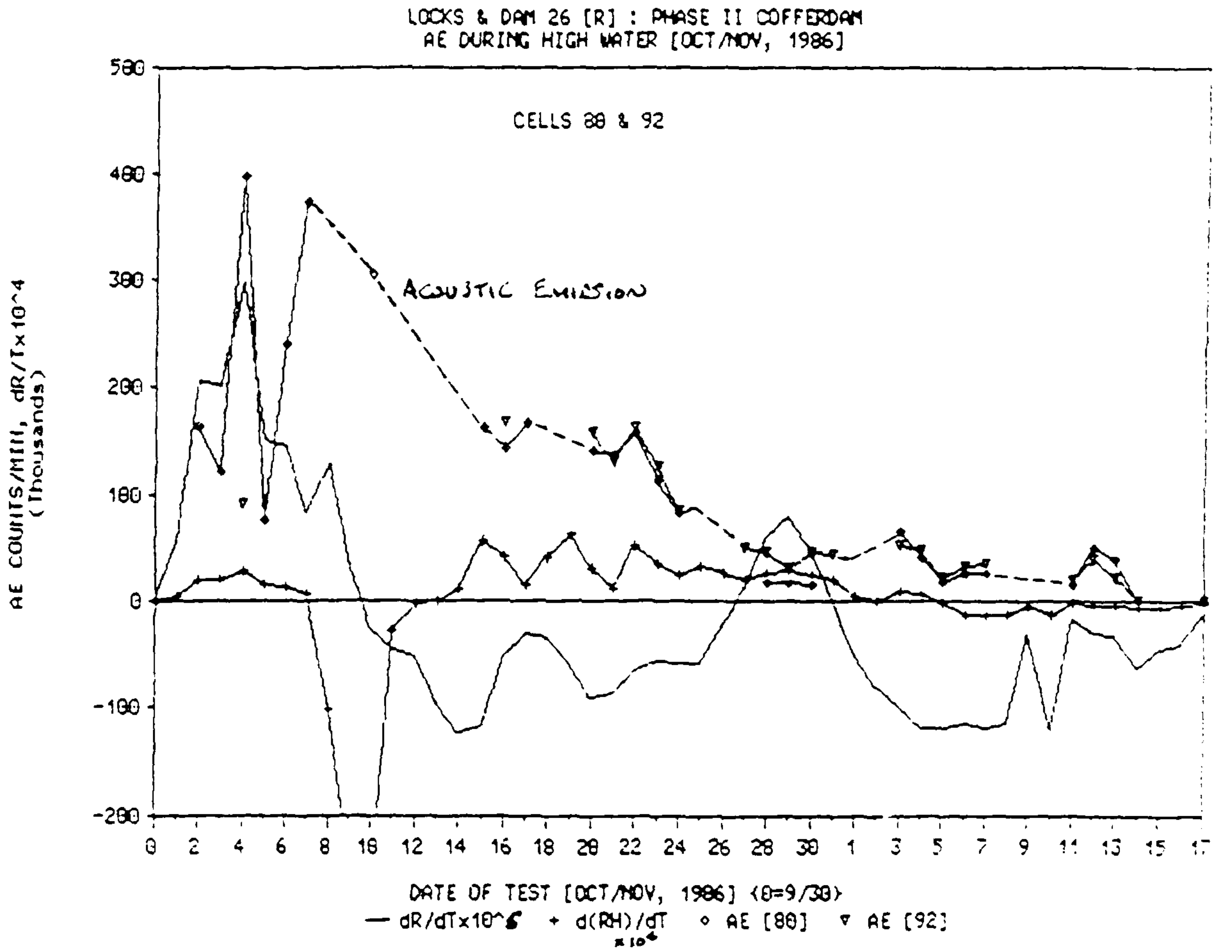


FIG 8.24 AE ACTIVITY, RATE OF CHANGE IN RIVER HEAD, RATE OF CHANGE IN RIVER ELEVATION

CELLS 80 & 92

OCTOBER-NOVEMBER 1986

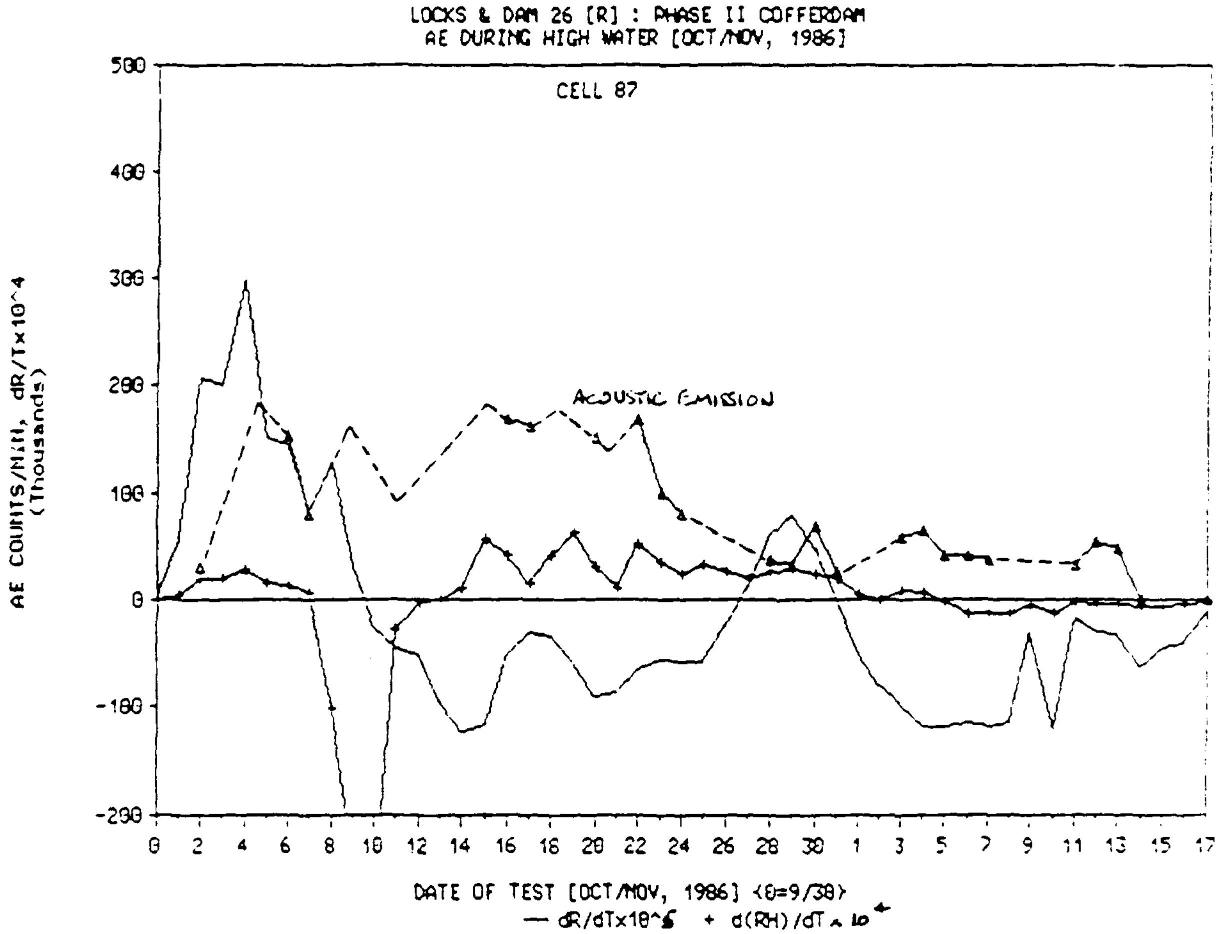


FIG 8.25 AE ACTIVITY, RATE OF CHANGE IN RIVER HEAD, RATE OF CHANGE IN RIVER ELEVATION

CELL 87

OCTOBER-NOVEMBER 1986

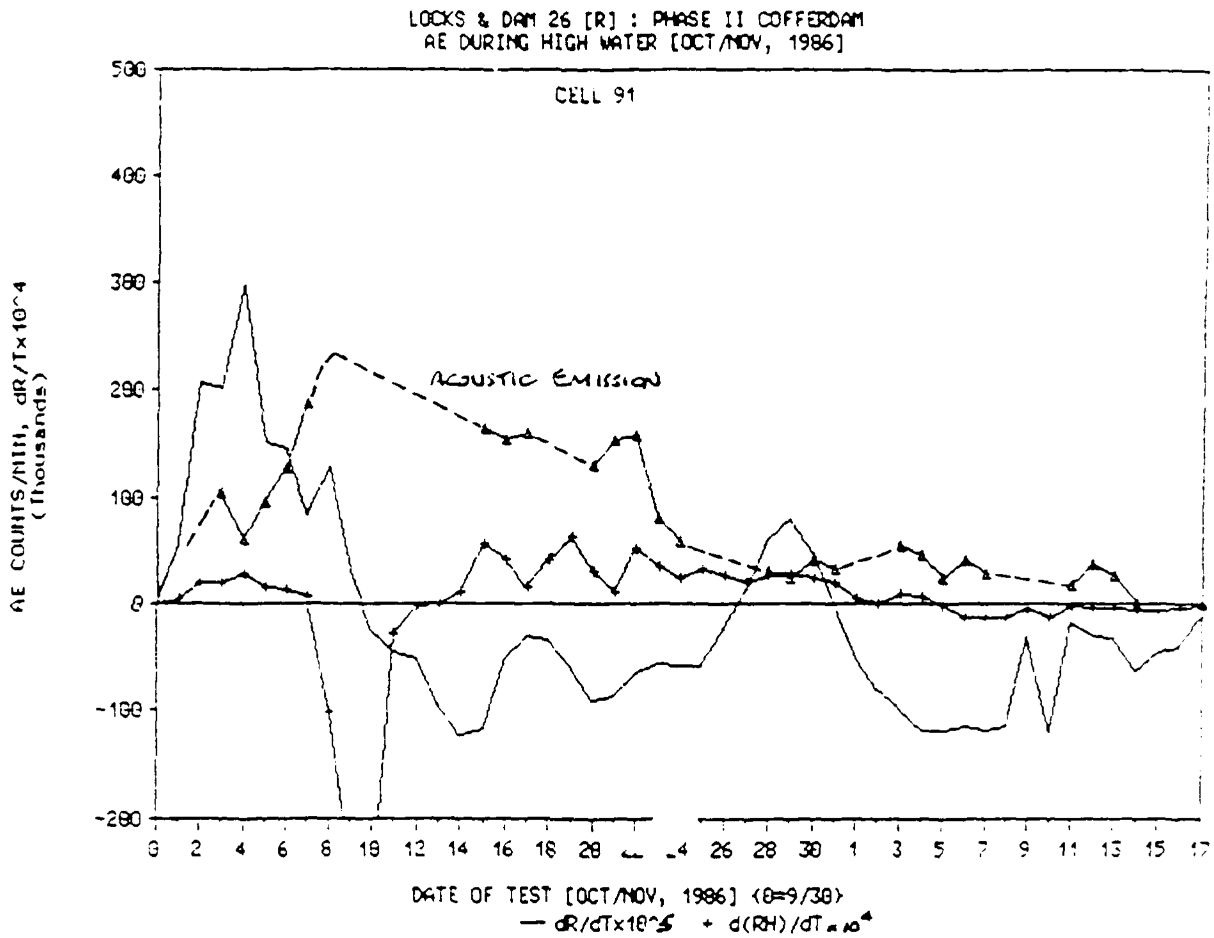


FIG 8.26 AE ACTIVITY, RATE OF CHANGE IN RIVER HEAD, RATE OF CHANGE IN RIVER ELEVATION

CELL 91

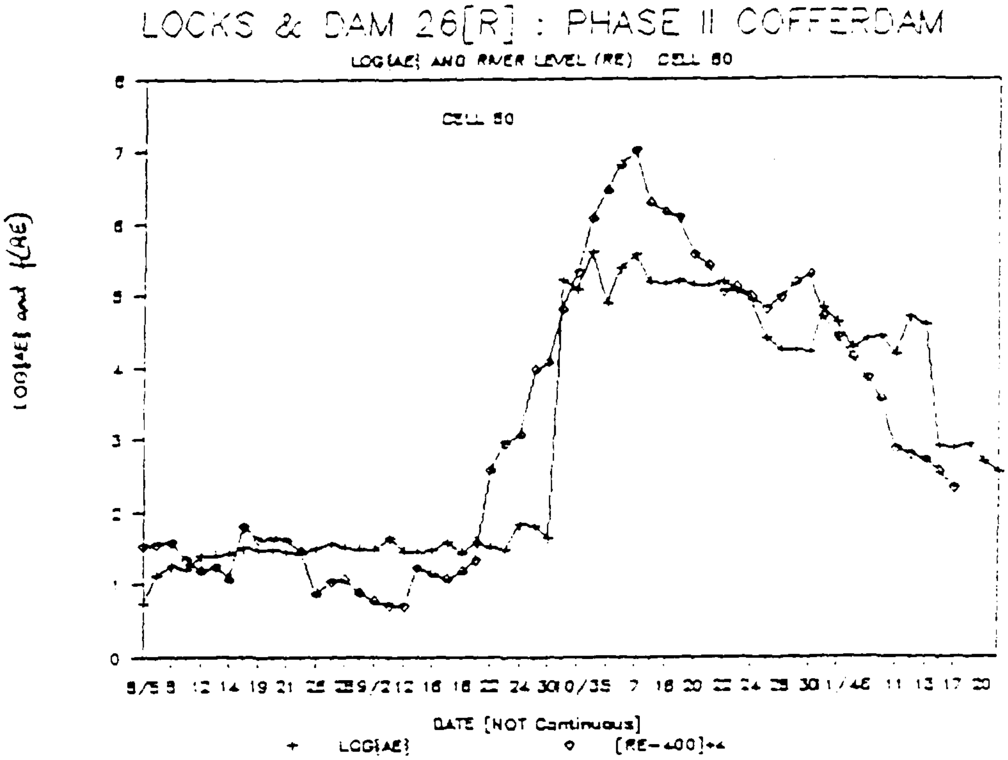
OCTOBER-NOVEMBER 1986

FIG 8.27 LOG AE ACTIVITY VS RIVER ELEVATION

LOG AE ACTIVITY VS RATE OF CHANGE IN RIVER HEAD

CELL 80

AUGUST-NOVEMBER 1986



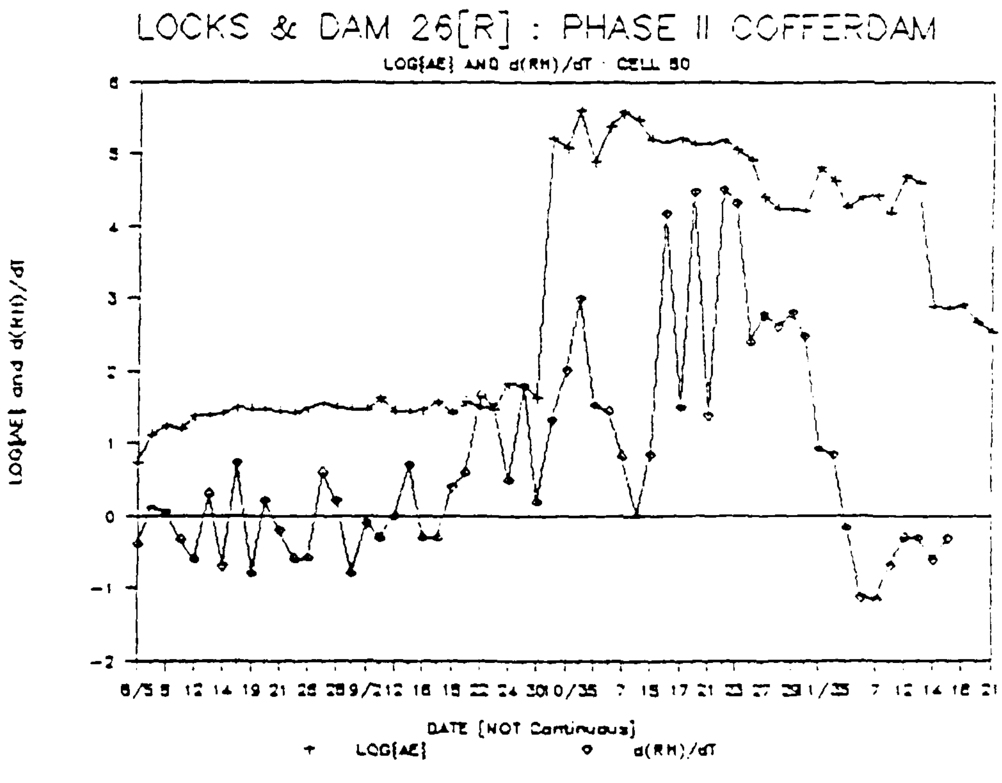
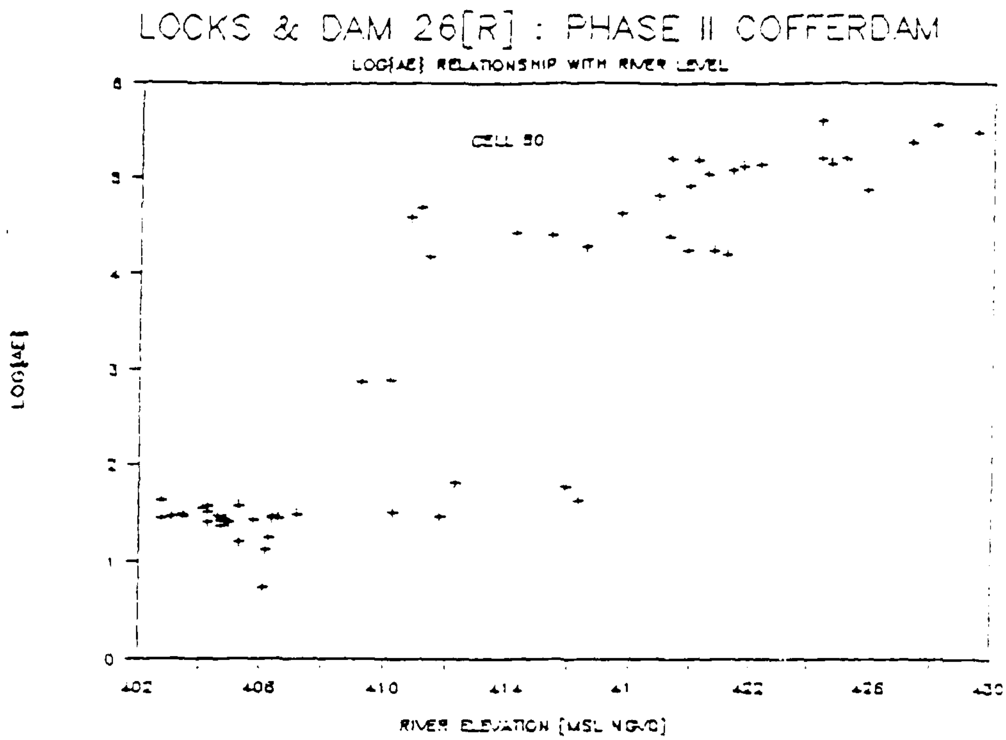


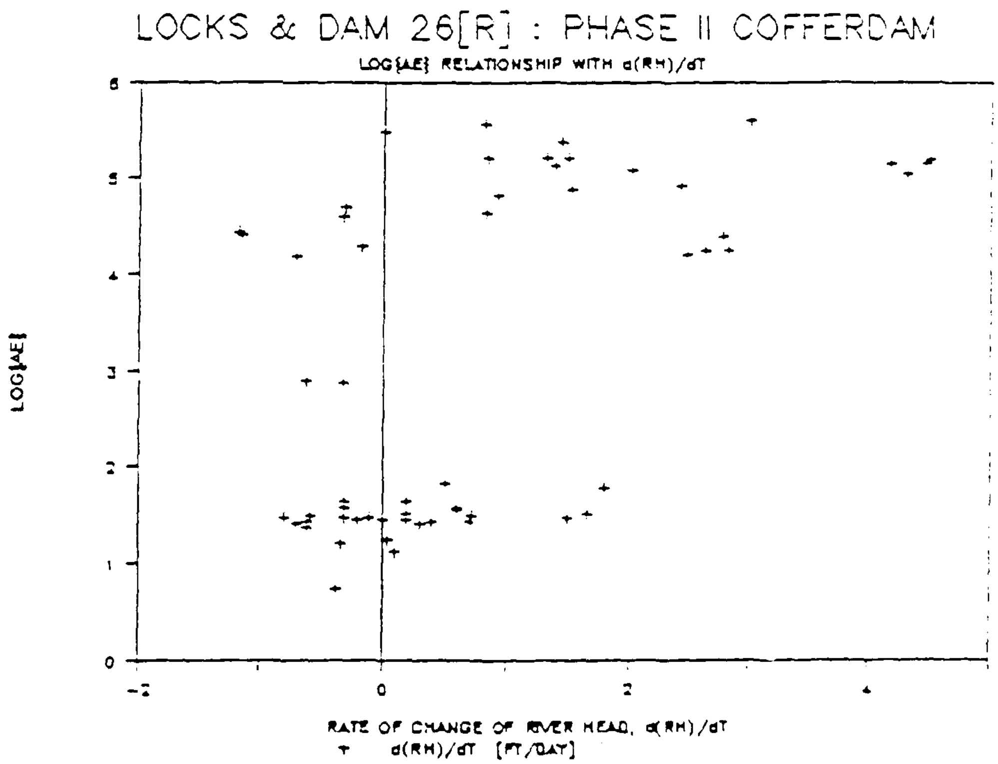
FIG 8.28 LOG AE ACTIVITY VS RIVER ELEVATION

LOG AE ACTIVITY VS RATE OF CHANGE IN RIVER HEAD

CELL 80

AUGUST-NOVEMBER 1986





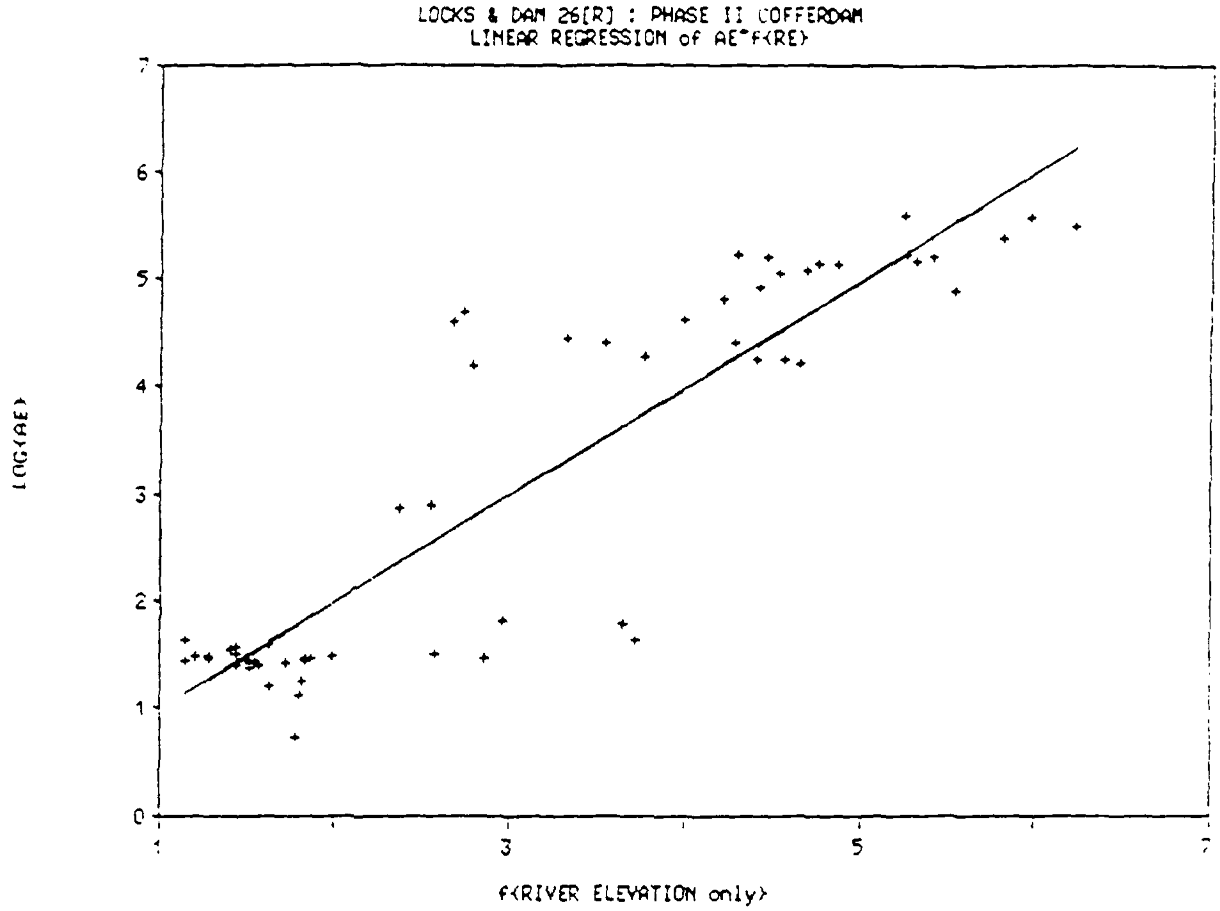


FIG 8.29 LINEAR REGRESSION

LOG AE ACTIVITY VS RIVER ELEVATION

CELL 80

AUGUST-NOVEMBER 1986

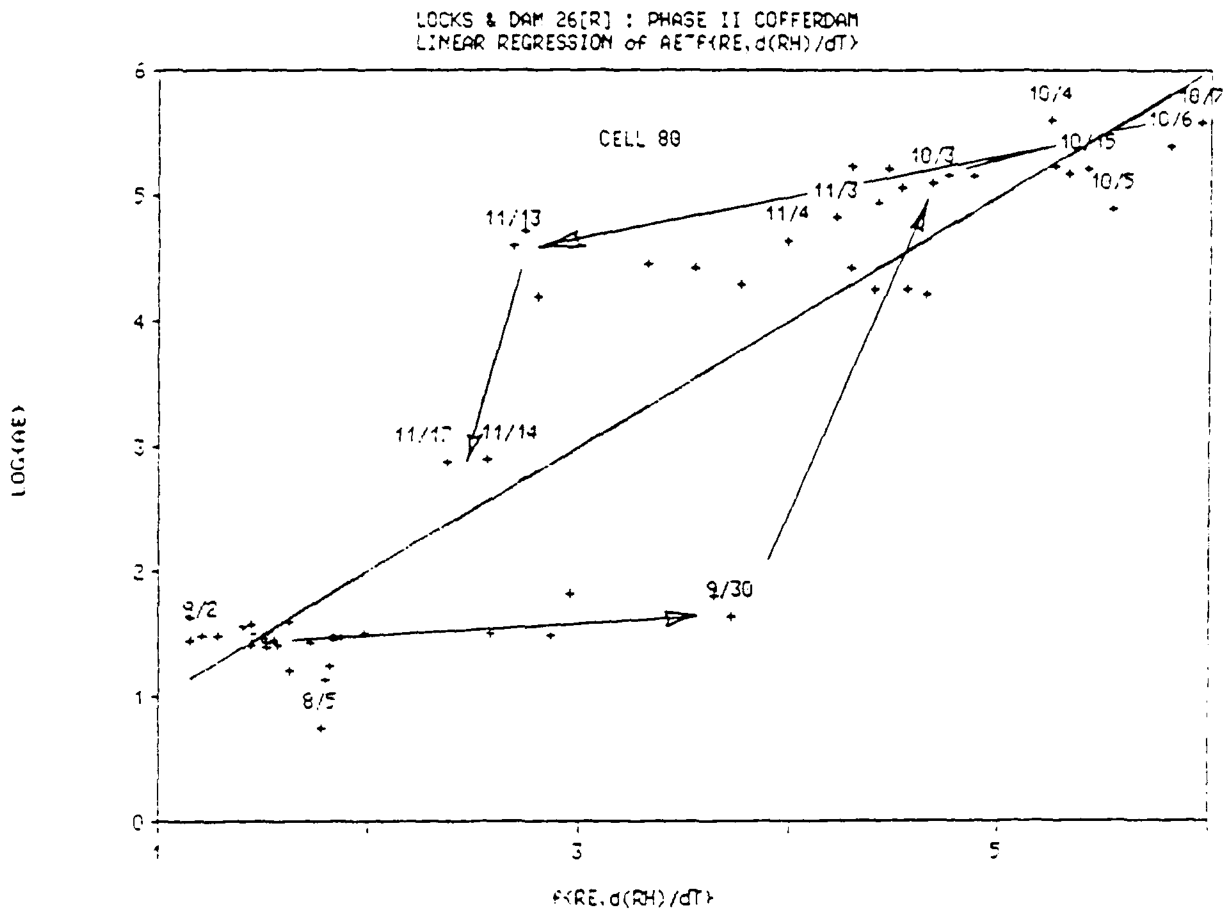
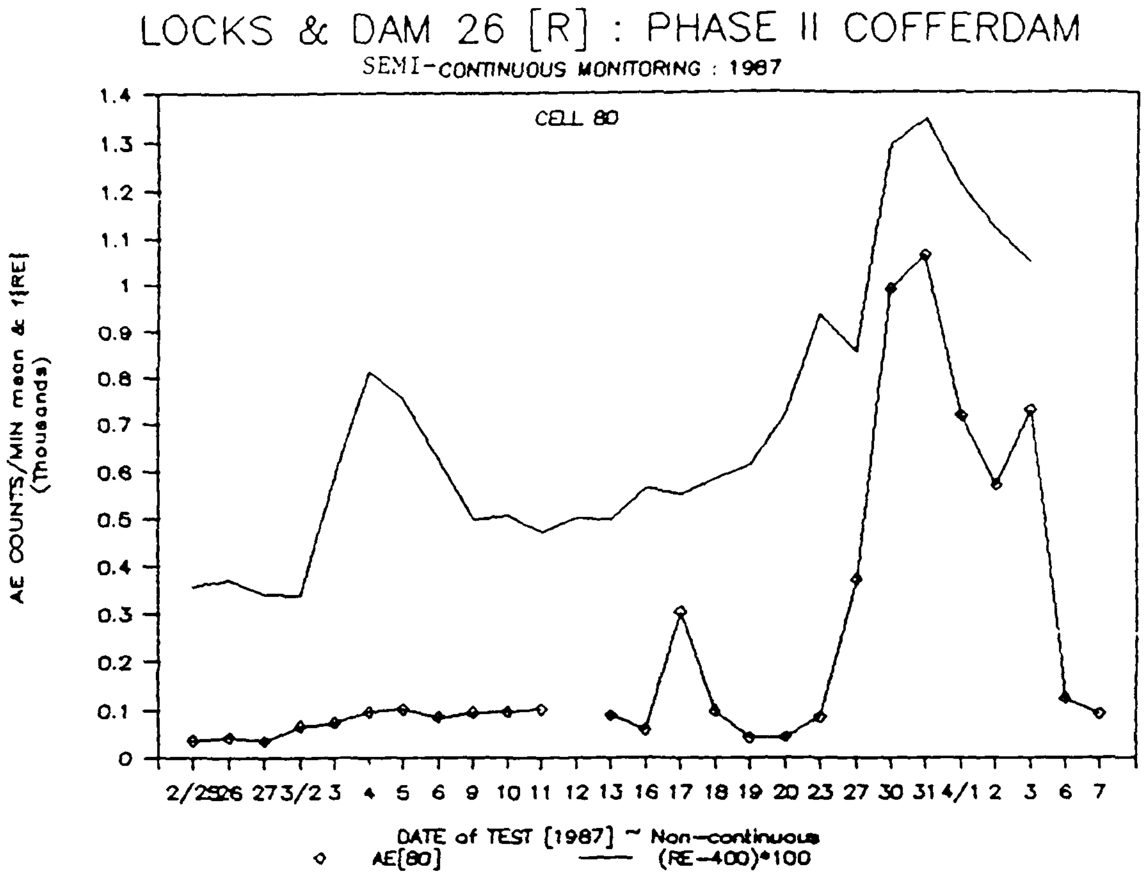


FIG 8.30 LINEAR REGRESSION

LOG AE ACTIVITY VS RIVER ELEVATION & RATE OF CHANGE IN RIVER HEAD

CELL 80

AUGUST-NOVEMBER 1986



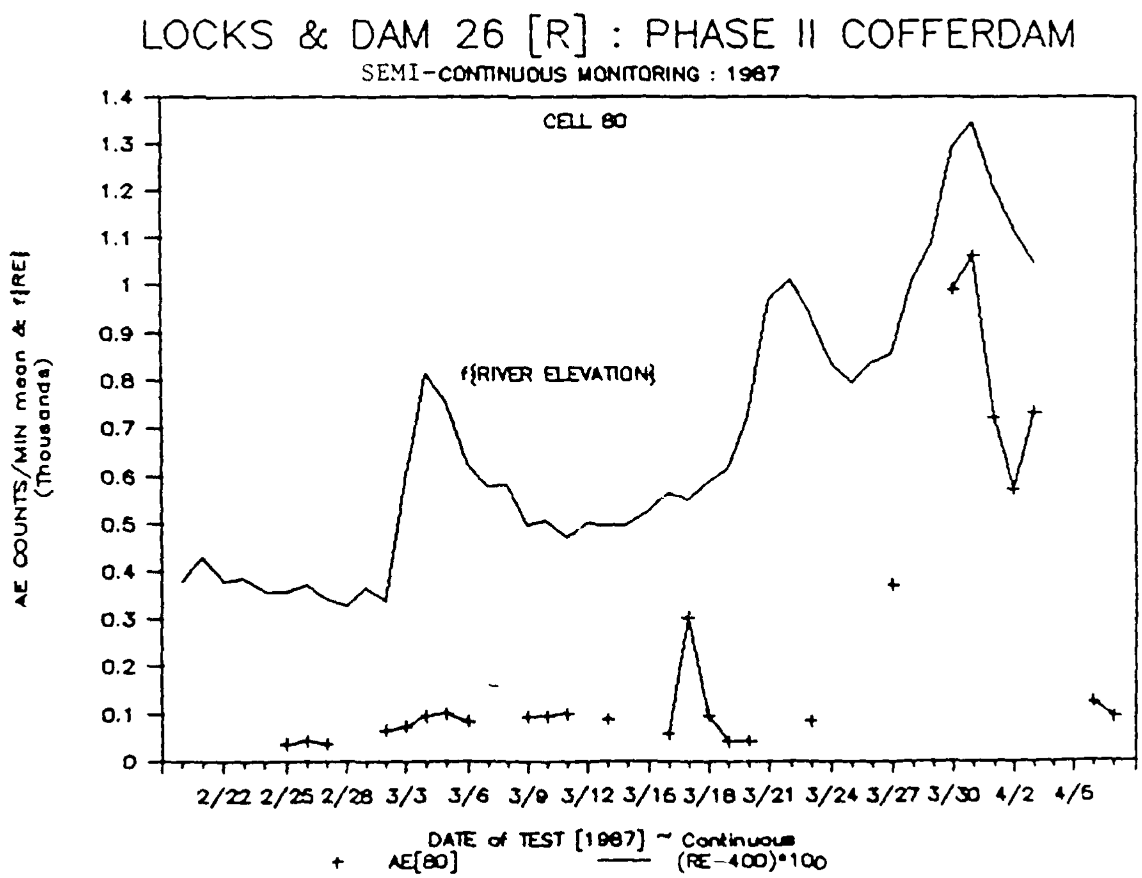


FIG. 8.31 AE ACTIVITY, RIVER ELEVATION
CELL 80 FEBRUARY-APRIL 1987

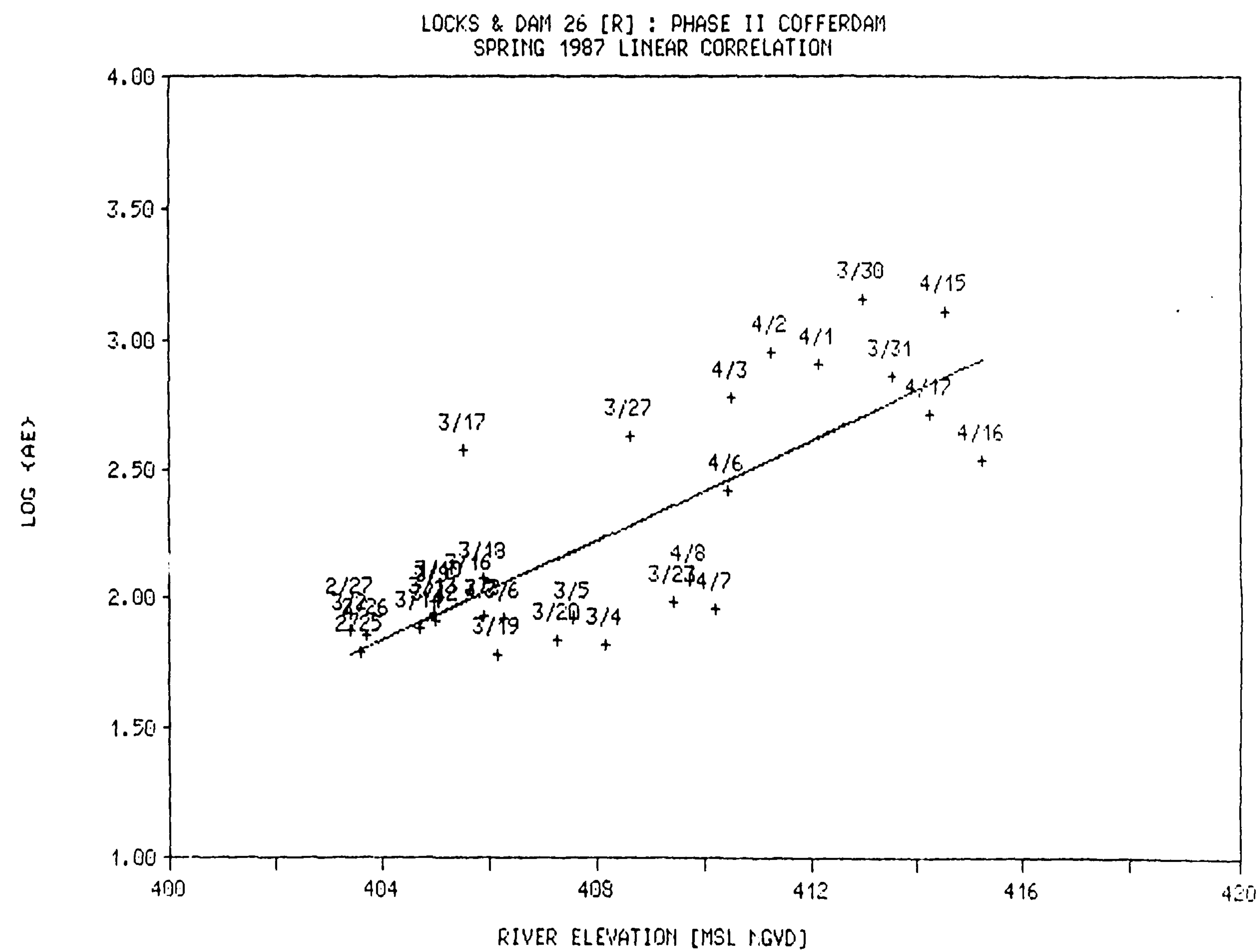


FIG 8.32 LINEAR REGRESSION

LOG AE ACTIVITY VS RIVER ELEVATION FEBRUARY-APRIL 1987

A-ARV A-Dump is ON

NON-CUMULATIVE

INTERVAL SUM

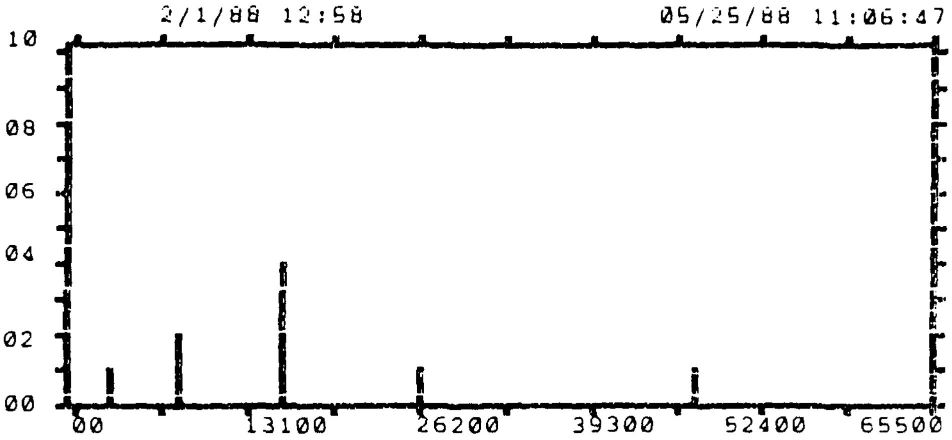
Events LTLF

CH 1

Test Point =262-524

Demand point = 0

GRAPH 1 OF 15



Time (Sec) LTLF CH 1

A-ARV A-Dump is ON

NON-CUMULATIVE

INTERVAL SUM

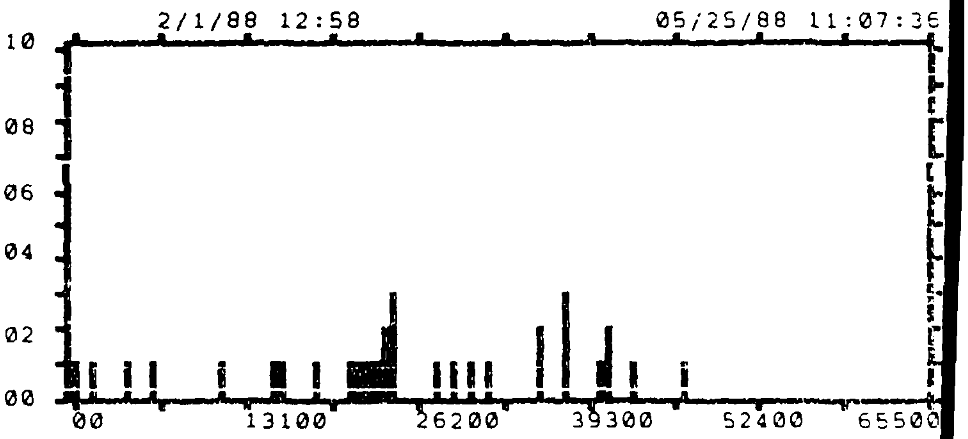
Events LTLF

CH 2

Test Point =262-524

Demand point = 0

GRAPH 2 OF 15



Time (Sec) LTLF CH 2

FIG 8.33 ATLAS 7016/3000

TYPICAL LONG-TERM COINCIDENCE PLOT

WG-76.30.S	WG-76.70.C
CH 01	CH 02

A-ARV A-Dump is ON

NON-CUMULATIVE

INTERVAL SUM

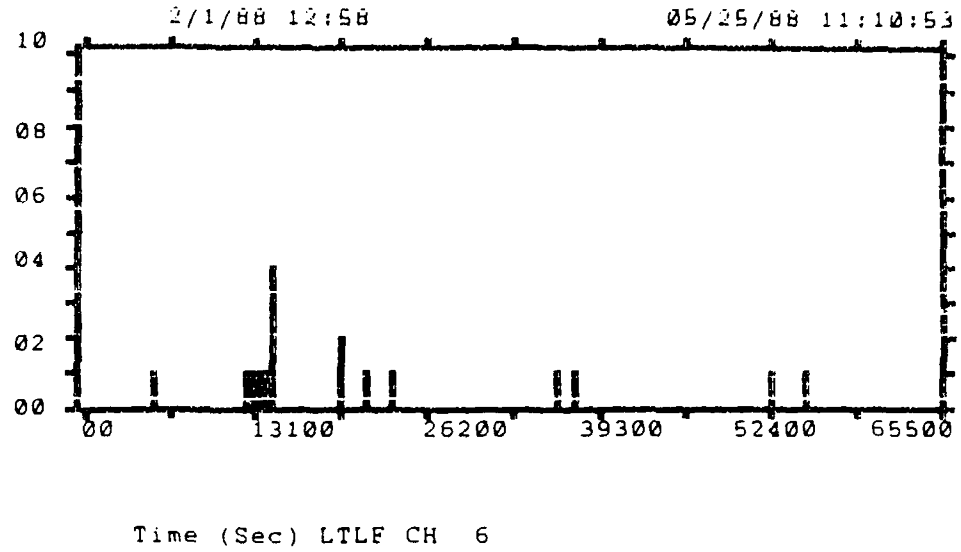
Events LTLF

CH 6

Test Point =262-524

Demand point = 0

GRAPH 6 OF 15



A-ARV A-Dump is ON

NON-CUMULATIVE

INTERVAL SUM

Events LTLF

CH 7

Test Point =262-524

Demand point = 0

GRAPH 7 OF 15

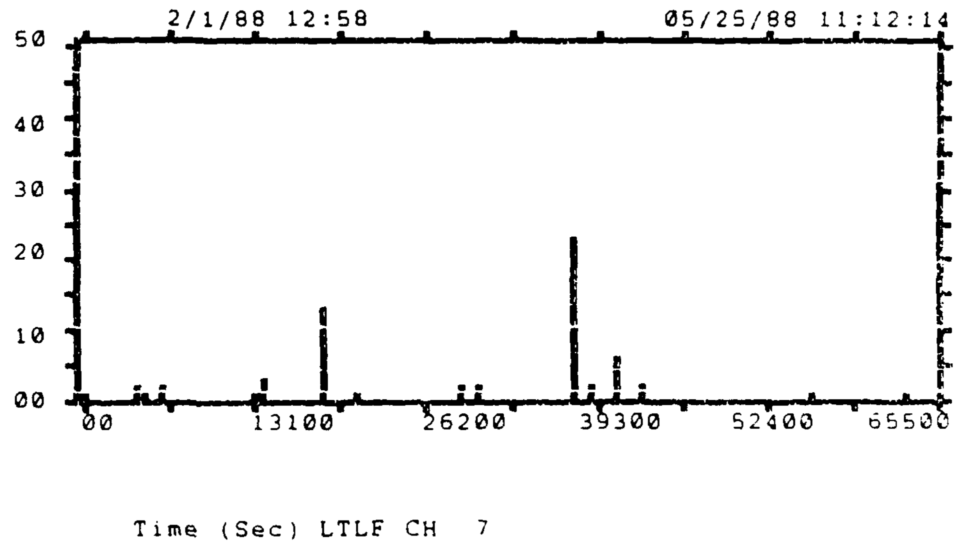


FIG 8.34 ATLAS 7016/3000

TYPICAL LONG-TERM COINCIDENCE PLOT

WG-77.50.C	WG-77.30.N
CH 06	CH 07

A-ARV   A-Dump is ON

NON-CUMULATIVE

INTERVAL SUM

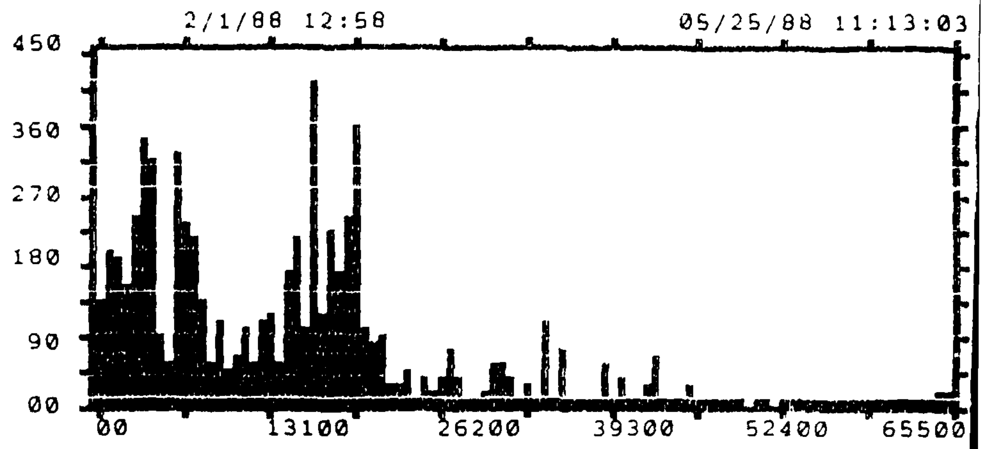
Events   LT~~##~~LF

CH   4

Test Point =ZLZ-524

Demand point =   0

GRAPH   4 OF 15



Time (Sec) LTLF CH   4

A-ARV   A-Dump is ON

NON-CUMULATIVE

INTERVAL SUM

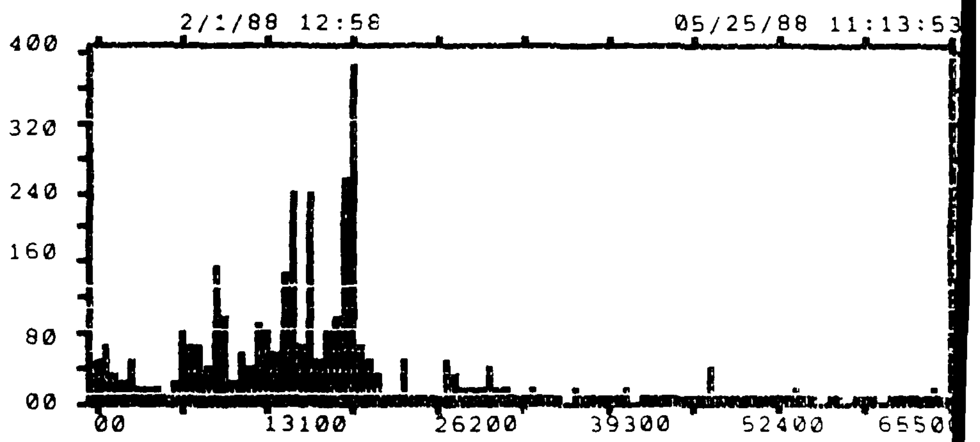
Events   LT~~##~~LF

CH   9

Test Point =ZLZ-524

Demand point =   0

GRAPH   9 OF 15



Time (Sec) LTLF CH   9

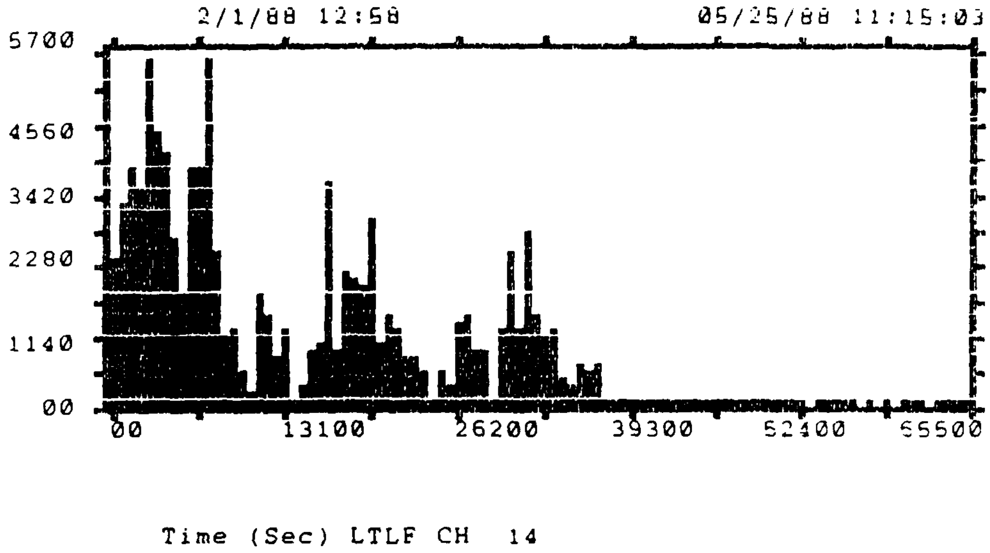
FIG 8.35 ATLAS 7016/3000

TYPICAL LONG-TERM COINCIDENCE PLOT

SP-76	SP-77
CH 4	CH 9

A-ARV A-Dump is ON

NON-CUMULATIVE
INTERVAL SUM
Events LT~~HT~~LF
CH 14
Test Point =262-524
Demand point = 0
GRAPH 14 OF 15



A-ARV A-Dump is ON

NON-CUMULATIVE
INTERVAL SUM
Events LT~~HT~~LF
CH 15
Test Point =262-524
Demand point = 0
GRAPH 15 OF 15

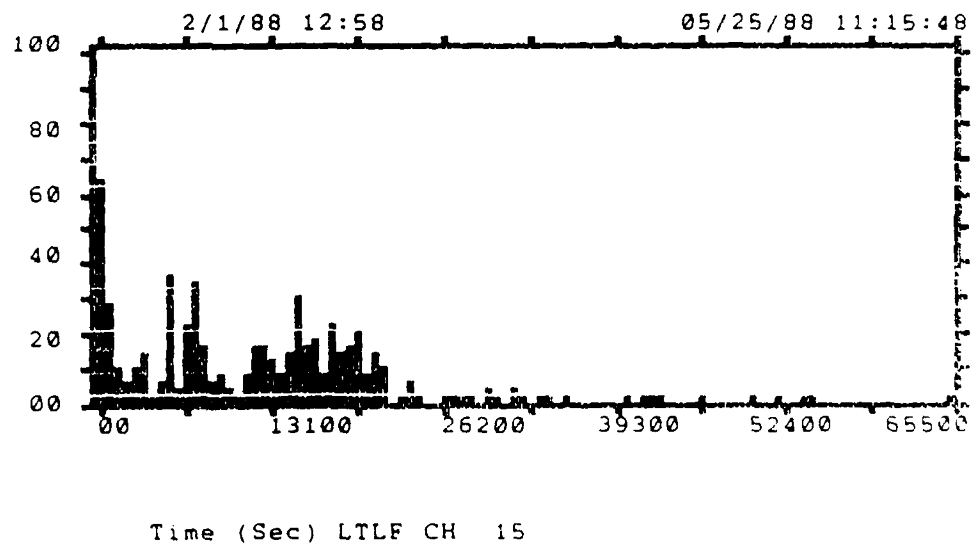


FIG 8.36 ATLAS 7016/3000

TYPICAL LONG-TERM COINCIDENCE PLOT

SP-79	SP-79/80
CH 14	CH 15

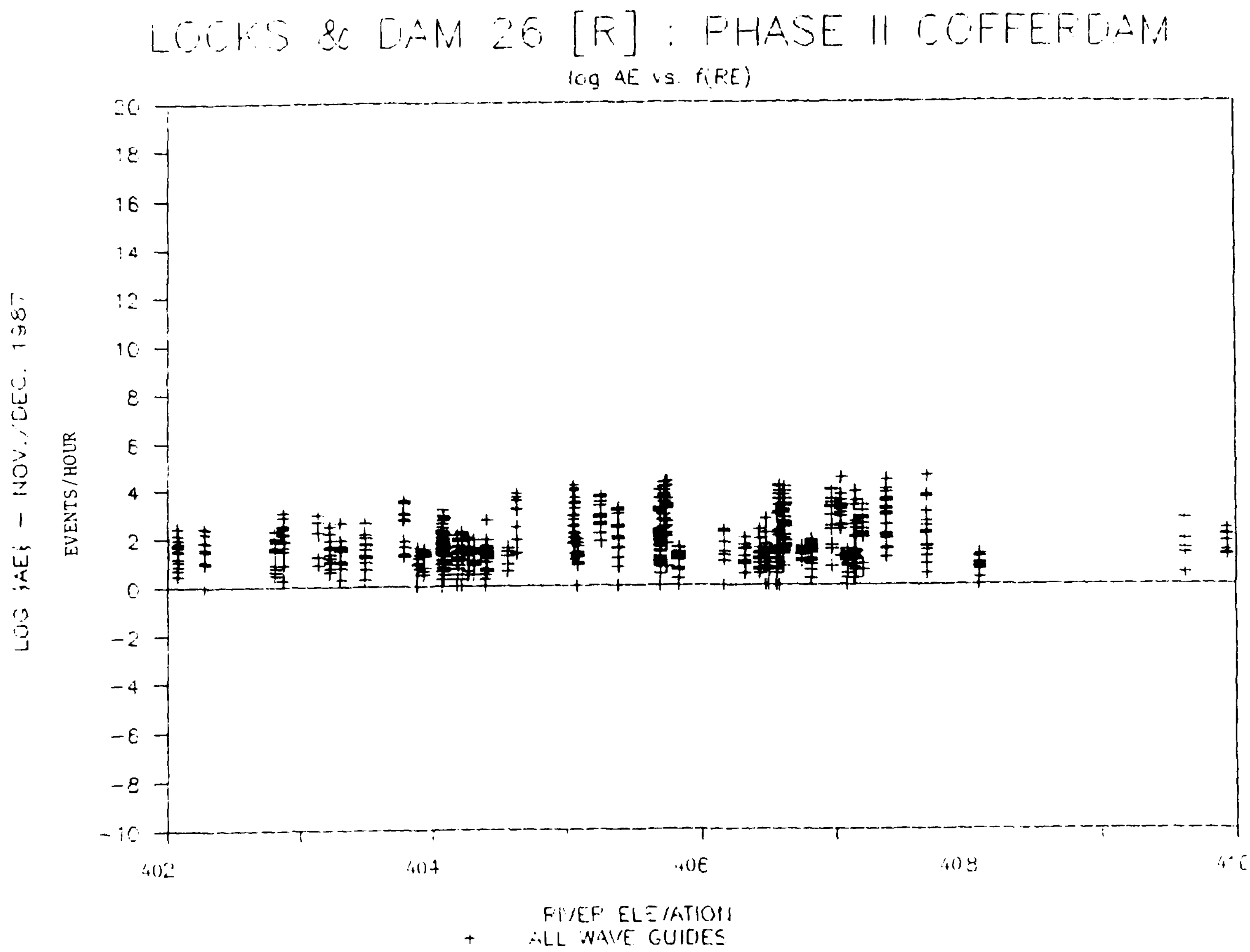


FIG 8.37 LOG AE ACTIVITY VS RIVER ELEVATION

ALL WAVE GUIDES NOVEMBER-DECEMBER 1987

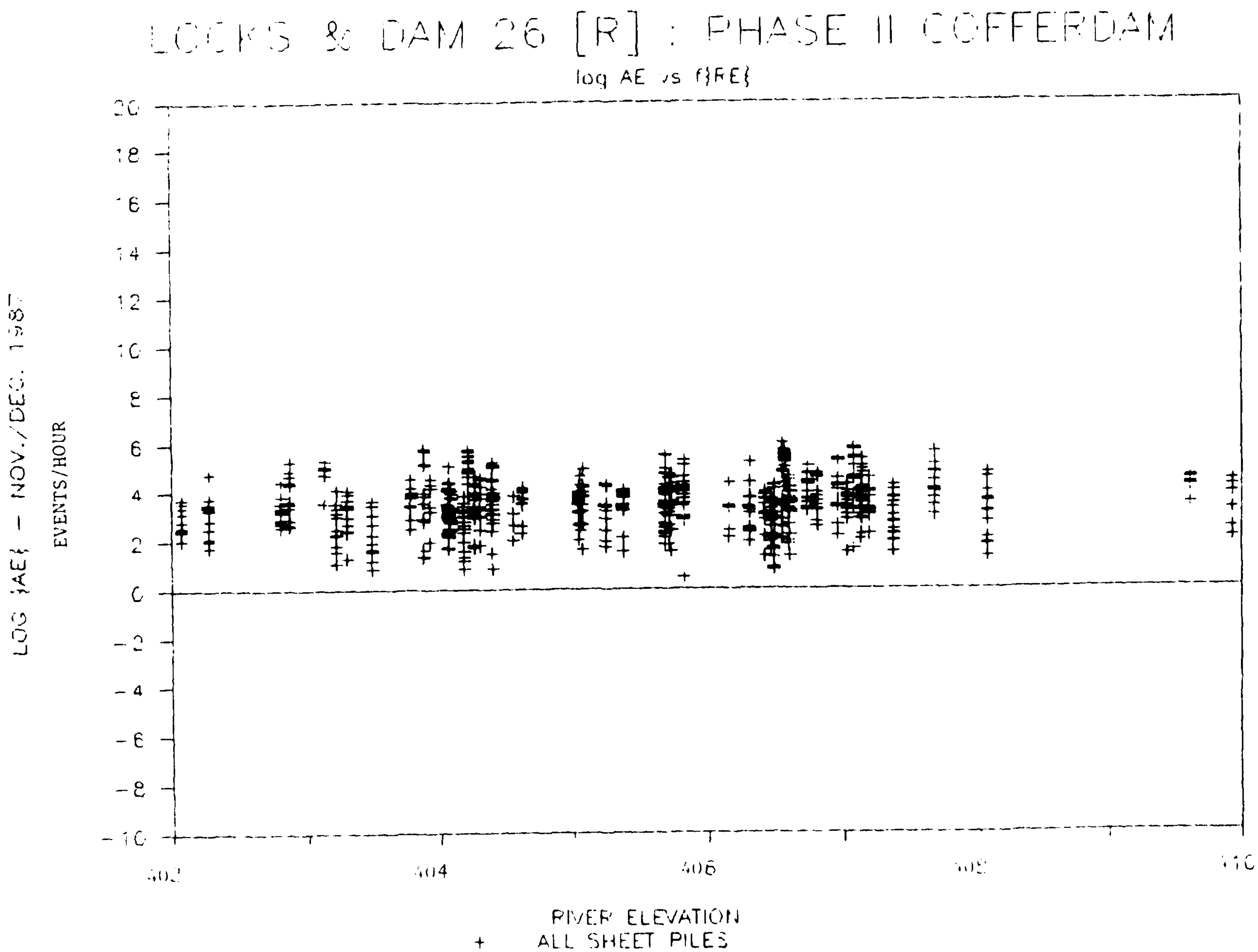


FIG. 8.38 LOG AE ACTIVITY VS RIVER ELEVATION

ALL SHEET PILES NOVEMBER-DECEMBER 1987

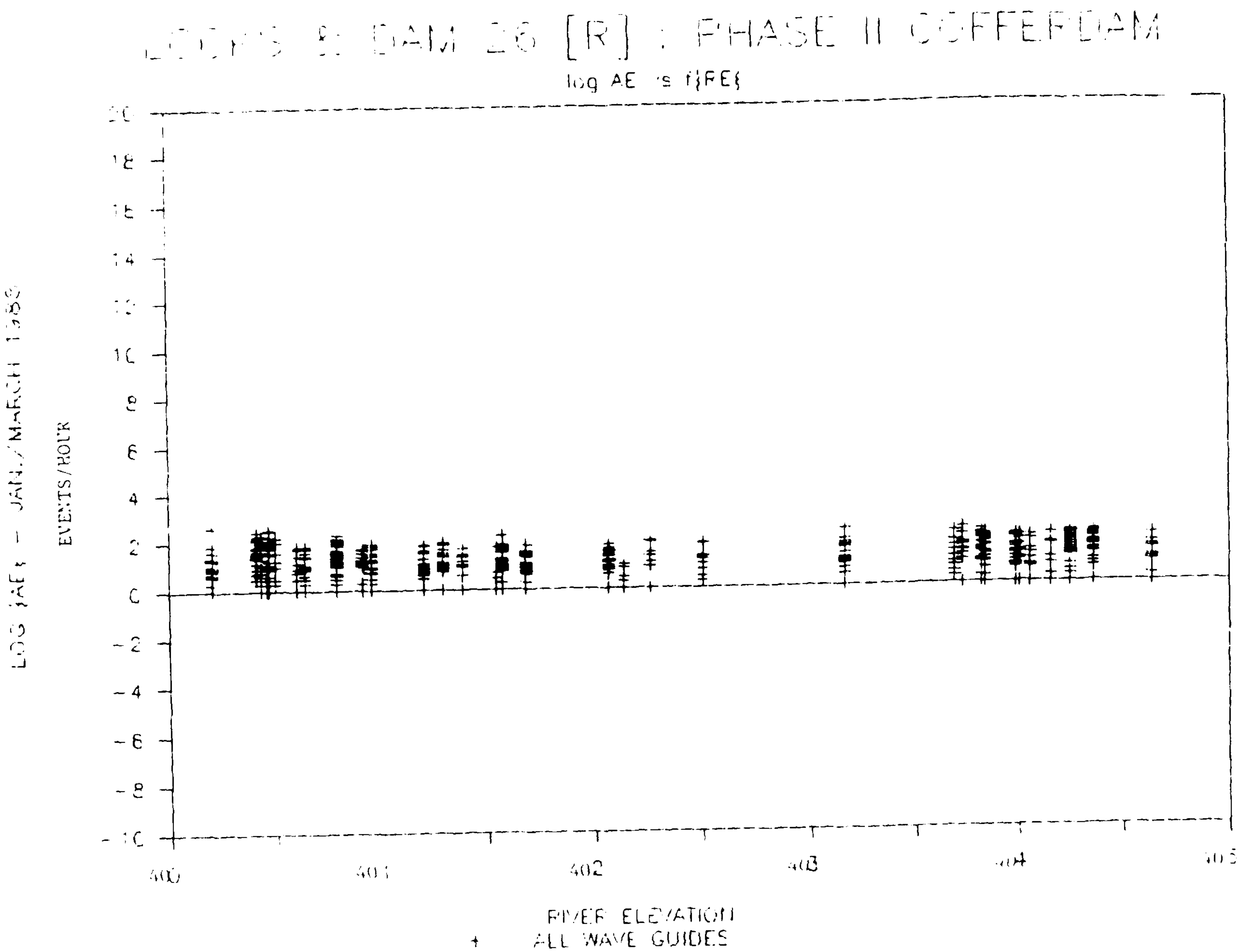


FIG. 8.39 LOG AE ACTIVITY VS RIVER ELEVATION
ALL WAVE GUIDES JANUARY-MARCH 1988

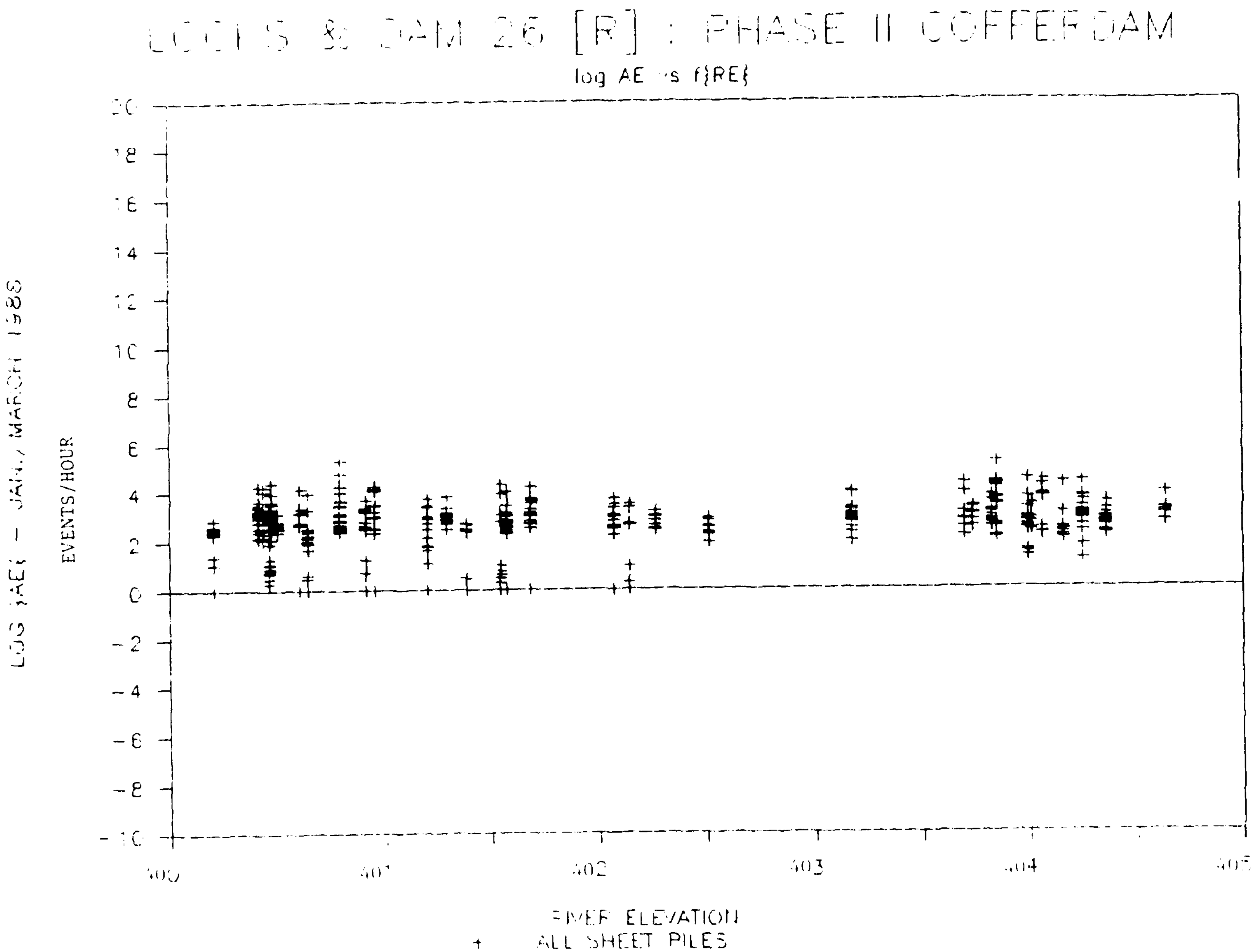


FIG. 8.40 LOG AE ACTIVITY VS RIVER ELEVATION

ALL SHEET PILES JANUARY-MARCH 1988

PHYSICAL ACOUSTICS CORPORATION

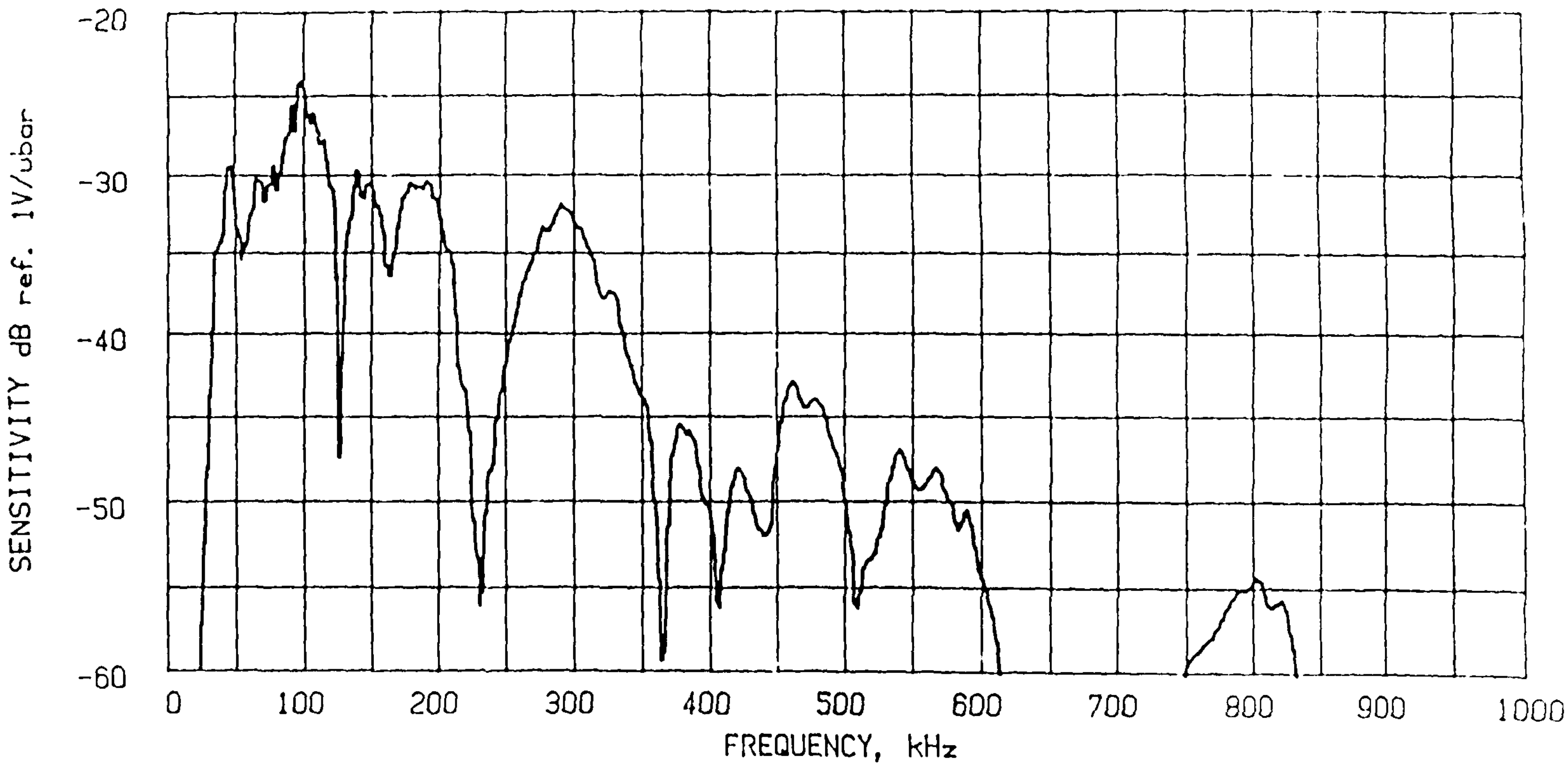
MODEL NUMBER: R8I

SERIAL NUMBER: 755

DATE: 9/10/87

TESTED BY: R O

DUNEGAN CORPORATION



This certifies that this sensor meets all performance environmental, and physical characteristics listed in applicable PAC/DUNEGAN specifications.

FIG 8.41 RESPONSE CHARACTERISTICS OF PAC ACCELEROMETER AT SP77 LOCATION AS GIVEN BY THE MANUFACTURER

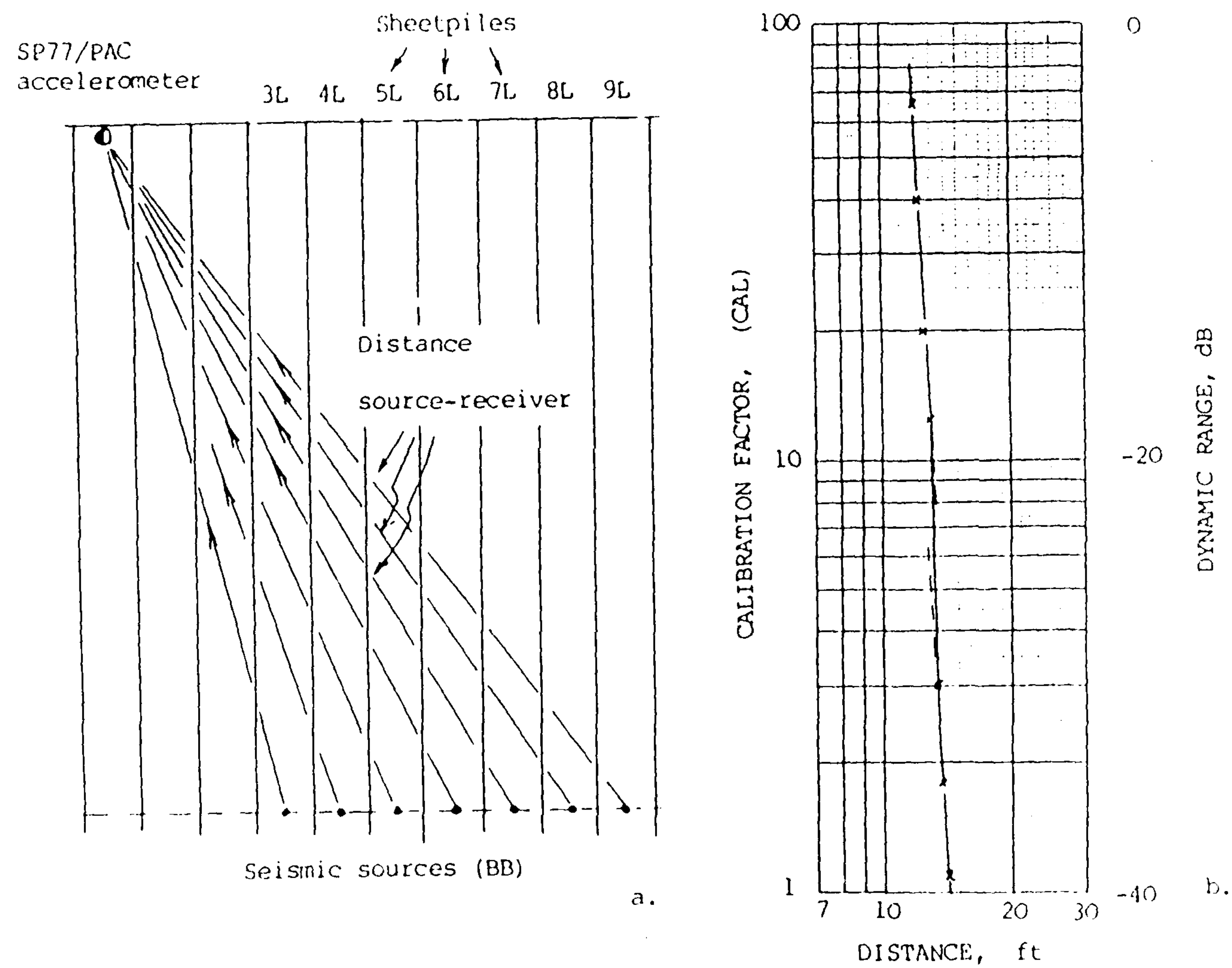


FIG 8 [illegible]ENUATION TESTS: (A) LAYOUT OF SOURCES (BB) AND THE PAC RECEIVER AT SP77: (B) ATTENUATION SLOPE VS DISTANCE FROM SOURCE TO RECEIVER

9.0 CONCLUSIONS

9.1 Assessment of Results

Based upon the data and analysis presented in the preceeding sections of this Study and previous experience in AE monitoring of earth structures, the level of acoustic emissions and their relationship to site conditions may be evaluated both qualitatively and in a broadly quantitative manner.

Six qualitative categories of assessment have been used, starting with no emissions, followed by low, medium, medium-high, high, and very high AE emissions, corresponding to full stability, then gradually decreasing stability to instability. These general categories represent the results of all the field measurements; from those made at low river elevations to those generated by the extreme high water of October/November 1986.

In order to quantify the above descriptions, reference was made to the two extreme conditions encountered at the site; namely low river stage when recorded emission levels were extremely low and maximum river stage when very high emissions, in excess of 100,000 AE counts per minute, were generated. Intermediate levels of AE activity were quantified as 100 or less counts per minute corresponding to low, up to 1,000 counts per minute for medium, between 1,000 and 10,000 counts per minute as medium-high, and above 10,000 counts per minute as high. The foregoing qualitative and semi-quantitative classifications and their corresponding site conditions and probable AE sources are given in Table 9.1.

9.2 Laboratory Tests

A laboratory investigation was made by the Corps of Engineers, Waterways Experiment Station, to assess the influence of density and effective confining pressure on AE signals emitted during triaxial compression tests on specimens of the granular soil which filled the cofferdam cells. It was observed that the stress/strain curves matched the curves of normalized deviator stress vs AE counts in the elastic range, that is at low stress levels and low AE emissions. These curves generally correspond to the low emission level AE category to be expected during low river stages at the site. The transition between the elastic and plastic zones of the stress/strain curve corresponds to the zone of medium-high emission levels. The high and very high ranges both occur in the plastic range of the curve. The laboratory curves appear to draw little distinction between the high and very high categories. A sharp contrast is noted in these categories from the field data, where the high range of AE emissions were generated while the river was rising to the highest level recorded during the Study and very high emissions occurred when that level was reached. This contrast is shown conceptually in Figure 9.1.

9.2.1 Differing Conditions in Laboratory and Field

In assessing the field and laboratory data it is important to consider the differing condition of the granular soil of the triaxial cell specimen and the site cell fill. The former was entirely in the sand range and was compacted very carefully in thin lifts to a relatively uniform density, while the latter was

sand and some gravel and was dropped into place with clam shell buckets. It is expected that considerable arching, resulting in loose zones, exists in the cell fill, particularly due to side friction from the sheet piles and larger particle sized material. Sand arching is unlikely in the triaxial specimen due to careful placement and confinement in a flexible membrane and the relatively small sized material. Apart from different granular soil densities and water content in the cell fill from top to bottom, significant variations almost certainly exist from the sides of the cell to the middle. As a result, the well-defined elastic/plastic behavior of the stress/strain curve in the laboratory is contrasted with a more transitional curve such as the conceptual depiction of field results shown in Figure 9.1.

9.2.2 Emission Generation

Previous investigations have shown that during deformation of granular soils, AE signals are generated as the soil grains readjust their positions and interlock into a new state. A period of equilibrium results even though the soil is sustaining a higher stress level and the emissions may remain temporarily constant before falling to lower levels. In some cases a deformation will be caused at a low stress level, far from failure, while in other cases the stress level may be near failure but without ongoing deformation and therefore only nominal acoustic emissions result. These conditions for sporadic and continuous emissions were represented by the laboratory test results and also by emissions

from the cofferdam sheetpile interlocks. This is the "Kaiser Effect" commonly found in metals, rock and other engineering materials. Stick/slip motion at the interlocks would cause sporadic emissions. If after reaching a certain level the signals become continuous, they should be interpreted as a warning of serious instability and possible failure conditions. However, a reduction in emission rate at constant load conditions would indicate equilibrium.

9.2.3 AE Limit

An attempt to develop an estimate of the AE limit from the laboratory test curves of Deviator Stress vs AE counts proved unsuccessful due to the granular nature of the cell fill which made the transition from high to very high levels of emission too short. Best judgement indicates the AE limit to be in the area of 100,000 plus counts per minute for a sustained period of time. Beyond this level the system is experiencing potentially serious deformation.

9.3 Concern Level

9.3.1 Structural Instability

The question arises, at what level of AE generation should the signals be considered a cause for concern? Assume a monitoring system similar to that described previously i.e., cofferdam cell sheetpiles and 30 to 70 foot long drill rods embedded in the cell fill used as waveguides monitored with 30 to 150 KHz sensors. Significant deformation could be expected at

the upper end of the high level of AE emissions. At that point, it could be too late for successful remedial action. Consequently, the concern level should occur in the medium-high emittive range (i.e., between 1,000-10,000 counts per minute). At this time data from other types of instrumentation should be examined. These would include survey data, piezometer and river levels, pile movement point (PMP) data, and slope indicator readings. Examination of data from other instrumentation would be especially important if medium-high to high levels of AE generation were recorded when river levels were relatively low. Under these conditions, the AE readings would have to be considered as a precursor of some degree of instability and a possible sign of continuous yielding and potential failure. At very high sustained levels of emissions, the structure could be in a critical state and visual precursors of failure should become obvious, i.e., sheet-pile splitting, rupture at interlocks, outflowing and loss of granular cell fill, major movements of cells or berms, etc.

9.3.2 Barge Impact

At the moment of barge impact against the outsite surface of the cofferdam, low frequency, high amplitude waves will be propagated along the cofferdam structure. Propagation of the waves via the connecting arcs would be to the cells on each side of the cell struck by the barge, albeit at a lower signal level, due to attenuation. The wave(s) would be propagated to adjacent cells on each side until they were completely damped out. This event would be spontaneously very emittive and momentarily in the very high

category, probably greater than 100,000 counts per minute. Accordingly, the stress will either be accommodated in the sheet piles, interlocks and cell fill or deformation will occur. The longer the AE signals remain at the high level, the more they indicate the potential for continuing instability and possible failure. Ordinarily, emissions due to deformation of the sand fill will tend to damp out. It is estimated that such damping will occur within approximately 15 minutes or so. Thus, both the rate and duration of emissions can be used to evaluate the severity of impact.

9.4 AE Monitoring System

The results of the Study described in the foregoing are in agreement with other investigations. They clearly indicate a correlation of acoustic emissions or AE signals with movement or deformation of the system; in this case, a cofferdam. The AE signals are generated by the strain induced in the sheetpile/cell fill structural system caused by external loads which also produce stress in accordance with Hookes Law. This correlation of AE generation with stress, and the corresponding sudden release of strain energy, lead to the conclusion that an AE system can be devised which will monitor the performance of an entire cofferdam. Such a system could also have applicability to other cofferdams or similar structures.

9.4.1 System Attributes and Details

The attributes of such a system should include reasonable availability of off-the-shelf equipment, relatively simple

installation, reliability of equipment operation and ease of data interpretation; that is, data output should be presented in terms which can be readily understood by field engineering personnel.

Such a system can be generally described as a series of individual monitoring stations throughout the cofferdam, each providing AE signals to a central recording unit. Signals received at the unit would be processed and interpreted by appropriate software which would display the results for action by an engineer/operator. Further sophistication of the system could provide remote reading and/or sensing capability which would permit the data to be reviewed and acted upon by persons distant from the site. This software could be relatively simple or quite sophisticated. It could display raw data and rely on the engineer/operator to interpret and act on it or it could analyze the data and suggest appropriate actions ranging in significance from routine, to warning, to critical in nature.

A suitable system for a structure, such as a cofferdam, would consist of a central multi-channel AE monitoring unit. Each of the channels would record AE emissions from a sensor attached to a single sheetpile at a spacing no greater than every fourth cell of the cofferdam. Additional stations could be located on cells that are positioned for more likely impact from barge traffic. It would be important to have one channel dedicated to a known "quiet" area as a reference point. The rationale for selecting every fourth cell is based upon an estimate that an individual cell cannot register significant movement without causing movement of adjacent connecting arcs and cells. The large forces generated

by high water or barge impact which the system would be designed to detect, will be likely to cause significant cell movements. Under these conditions it is anticipated that the recorded AE events per minute would be several orders of magnitude greater than those induced by normal river levels and other routine activity in the area. The sharply increased AE signals recorded during the high water period of October/November, 1986, clearly support this conclusion. During the high water period, recorded AE counts per minute varied from 80,000 through 400,000 as shown in Figure 8.22. This may be contrasted with Figures 8.8 through 8.10 which show the AE signals recorded during the quiet low river levels in August/September, 1986. These were less than 100 counts per minute.

9.4.2 Sensors

It is anticipated that the frequency distribution of AE signals resulting from high water and barge impact would be substantially different. The signals engendered by high water are best recorded in the range of 20 to 60 kHz while those resulting from barge impact would be much lower; less than one kHz and quite possibly less than 100. In order to monitor and record signals from a significant (damaging) barge impact, a one kHz geophone would be utilized. Once the signal leaves the sensor (geophone), it would be carried to a central unit by a continuous cable. At the central unit, if the geophone signal was of sufficient magnitude, it would set off both a warning siren and a warning light. These could be located in the guard station and be

operable on a continuous 24-hour basis. Here the length of the continuous cable exceeded 1,000 feet, a buffer amplifier would be used to maintain signal strength.

A standard narrow band 30 to 60 kHz sensor would record the higher frequencies associated with structural deformation, while a geophone would be installed to monitor the very low frequencies. The signal from these sensors would be carried to the central unit by a separate cable, as described above.

9.4.3 System Deployment

As indicated above, a typical system would consist of a central recording unit and a series of monitoring stations as required by the size and configuration of the structure to be monitored.

The central unit would be housed at a convenient location on the cofferdam. The enclosure could be a standard construction trailer or similar structure and should be cooled in summer and heated in winter. It should also provide shelter and shield the equipment and its operators from exposure to the elements and dust. In order to ensure continuous operation of the warning system, provision should be made for an uninterruptible power supply (UPS). The UPS would ensure that the system would continue to operate during a general or localized power failure. If remote readout of the AE generation is considered desirable this can be accomplished over a standard telephone line. All cables from monitoring stations to the central recording unit would be protected and where possible, run underground in direct burial

mode. Each sensor would be attached to a sheetpile and enclosed in a protective enclosure below the top of the fill. The enclosure would be insulated to isolate the sensor from ambient and cultural noise or minor barge impact producing low signal levels.

9.5 Phase III Cofferdam Warning System

The general arrangement of the Locks & Dam 26 (R) Phase III cofferdam is shown in Figure 9.2. A barge impact warning system for this structure would consist of sensors installed on the sheet piles of cells 99, 92, 102, 104 and 106. These sensor locations would effectively record AE emissions generated by barge impact on any cell of the upstream arm of the cofferdam. The overall layout of the cofferdam and the main lock make the possibility of such an impact occurring elsewhere on the cofferdam, very unlikely.

Additional sensors required in a general warning system for possible distress caused by hydrostatic forces during high river levels, construction activities or for other unanticipated reasons would consist of sensors located at cells 76, 78, 80 108, 110 and 112.

The central processing unit would be housed in an enclosure as described in the foregoing, located on cell 82. From that location a telephone line would transmit the warning signals to an appropriate location or locations, such as the guard station.

Each of the five monitoring stations on the upstream arm (cells 99, 92, 102, 104 and 106) would have either wide band sensor or a 60 kHz sensor plus a one-kHz geophone. In either case

each station would require two channels at the central unit for a total of ten. The remaining six stations would record on one channel each, thus making a total of sixteen required channels.

The above general description of a warning system for the Phase III cofferdam is intended to be conceptual only. However, should such an installation be undertaken, it should be possible to expand it so that a practical, operational system is established.

9.6 Waveguide Type

Two general types of waveguide were utilized in the Study; the individual sheetpiles of the cofferdam cells and standard AW drill rods embedded to differing depths in the cell fill. Each has its advantages and disadvantages as described below.

Sheetpile monitoring stations are simple to install and they record AE signals from a wider area, and thus are considerably more sensitive than steel rods embedded in cell fill. Due to their exposed situation, sheetpiles are more responsive to cultural and ambient noise such as that from rain, wind, river ice, marine sonar, construction activity and similar AE sources. They would be the best choice for use in monitoring movement of the cofferdam due to the hydrostatic forces from differential river head and barge impact.

Steel rods used as waveguide monitoring stations are difficult and expensive to install since they require the embedment of steel rods to differing depths in the cell fill. They disrupt traffic and require cable to be placed underground to the edge of the cells. They do screen out much of the cultural noise of rain,

wind, river ice and sonar which affects the sheetpiles. They can also allow a better estimate of the depth at which AE activity is occurring if waveguides of differing lengths are installed. However, they tend to record emissions created by construction equipment as it passes over the cells in which they are installed. The levels of AE activity recorded at steel rod waveguide stations were much lower than that at sheetpile stations. This is probably due to the much smaller zone of material in contact with the drill rod than the sheet pile, and the smaller cross-sectional area of steel conveying the AE signals.

The recommended waveguide for use in the system described in Sections 9.4 and 9.5 is the sheetpile. Apart from the reasons given above, they exist as part of the structure, have greater sensitivity and proven applicability to the measurement of AE associated with hydrostatic load and/or impact on cells. Sheet-piles are also more effective in detecting AE activity related to adjacent cells and connecting arcs.

9.7 Summary of Conclusions

Previous investigations have shown AE monitoring to be an effective means of evaluating the stability of earth structures. The specific applicability of AE monitoring to cofferdams has been demonstrated through the extensive measurements undertaken as part of this study. In fact, AE monitoring offers a practical method for real-time monitoring of cofferdam stability, and timely detection of potentially dangerous barge impacts. More importantly, acoustic emissions begin to increase in advance of

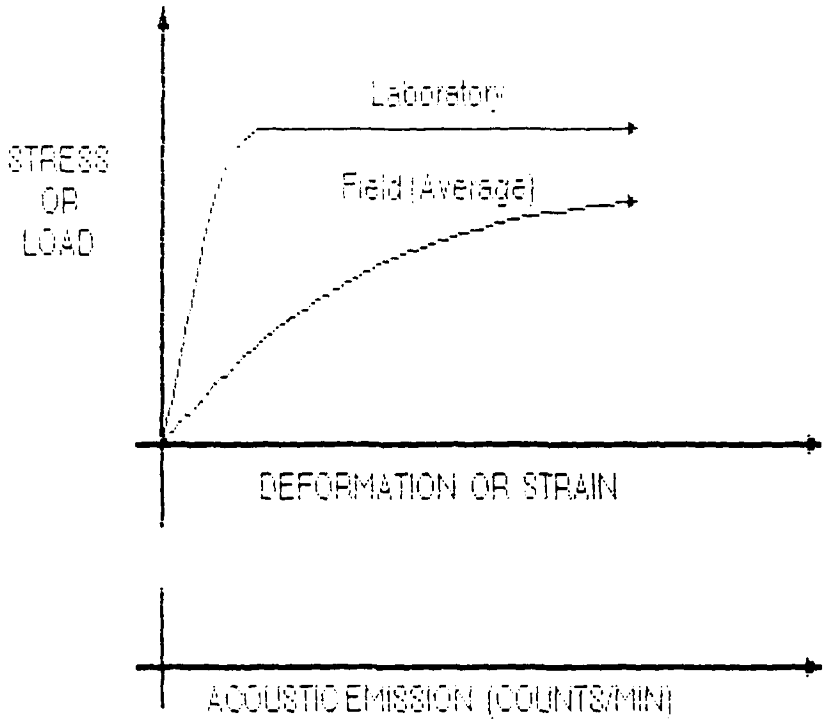
detectable movement or failure, providing advance warning of developing problems, much before they would be indicated by standard techniques such as optical survey or inclinometers.

Thus, a properly-designed and installed AE monitoring system will improve the safety of a given cofferdam structure. Furthermore, the more detailed analysis of cofferdam response to loading that is possible through AE monitoring may lead to improved cofferdam design in the future.

TABLE 9.1

QUALITATIVE/QUANTITATIVE ASSESSMENT

QUALITATIVE ASSESSMENT (RELATIVE)	QUANTITATIVE CATEGORIES (AE COUNTS/MINUTE)	SITE CONDITION	PROBABLE AE SOURCE
No emissions	-0-	Equilibrium	-
Low emission level	0 - 100	Low water level; elastic region	background
Medium emission level	100 - 1,000	Medium water level; elastic region	initial loading
Medium-high Emission Level	1,000 - 10,000	Medium to high water level; elastic region	moderate deformation
High emission level	10,000 - 100,000	High to very high water level; plastic region	significant deformation
Very high Emission level	>100,000	Close to over topping sheet piles; potential system instability; approaching failure region	continuous deformation



CONCEPTUAL RELATIONSHIP OF STRESS/STRAIN AND ACOUSTIC EMISSION

NOTE: ABOVE CURVES ARE CONCEPTUAL DEPICTIONS OF THE RELATIONSHIP OF STRESS/STRAIN AND ACOUSTIC EMISSIONS. THEY WERE NOT DERIVED FROM RECORDED DATA.

FIG. 9.1

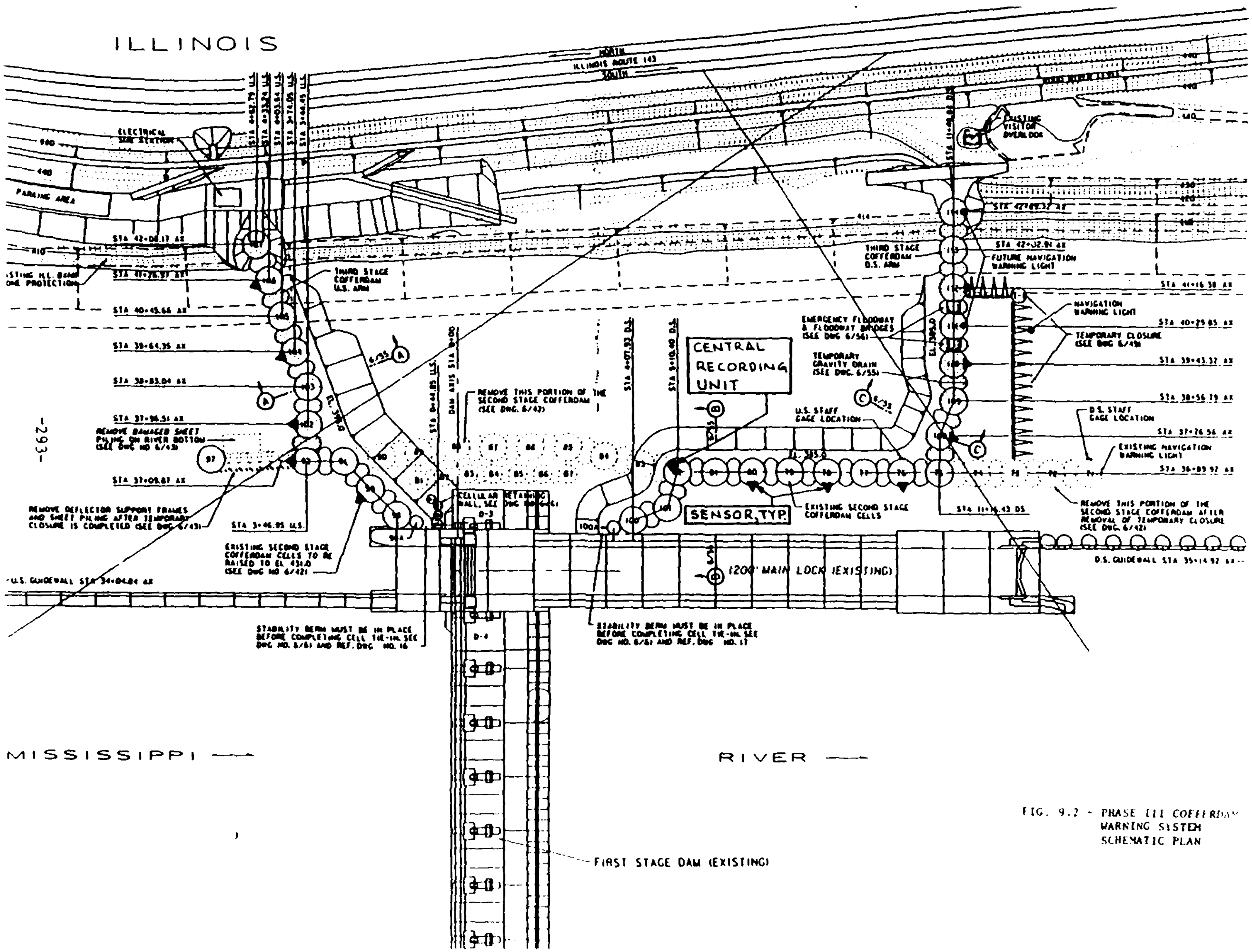


FIG. 9.2 - PHASE III COFFERDAM WARNING SYSTEM SCHEMATIC PLAN

10.0 RECOMMENDATIONS

The successful application of AE theory and practice during the two year period of the Study and the excellent correlation of acoustic emission levels with differential river head has been documented throughout this Report. Section 9 discussed and suggested the conceptual details of an AE system which can provide real time monitoring of cell movement, consequent stress and precursive signals warning of reduced local stability of the cofferdam structure. The system can also provide a real time barge impact emergency warning system. Not only can the latter system record and identify an impact event, but it can also be designed to determine the approximate magnitude and location of the collision and possible degree of damage to the cofferdam cells. The accuracy of the impact location can be further refined by the use of more sensors at closer intervals.

It is recommended that further AE measurements be made at different river levels, and that a continuous monitoring system be installed to enhance the safety of the Phase III cofferdam. Additional data and analysis are necessary so that variations, such as cell type, river bottom condition and geology at different Corps of Engineer sites can be properly assessed. Such studies would allow the AE results from Lock & Dam 26 (R) to be applied to other and different cofferdams, involving a wide variety of site conditions, differing layouts, geometrics, and fill materials.

It is also recommended that a system such as that described herein be installed in the Locks & Dam 26 (Replacement) Phase III cofferdam where it can serve as a real time in-situ warning system. If the Phase III installation functions successfully, it is further recommended that the model be adapted to other cofferdams at other locations. This last recommendation is qualified by the recognition that different river conditions, structure type, configuration, foundation materials and river bed geology may require modification of the design of the AE monitoring system. The baseline AE data, however, has clearly been defined by the results of this Study.